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SYSTEMATIC AND INTEGRATED APPROACH TO TROPICAL CYCLONE TRACK FORECASTING IN THE NORTH ATLANTIC

by

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This study is the application of the meteorological framework of Carr and Elsberry to the North Atlantic. All North Atlantic tropical cyclones from 1990-1994 are examined using 500 mb Navy Operational Global Atmospheric Prediction System streamline and isotach analyses, geostationary satellite imagery, and the tropical cyclone best track information. Application of the Systematic Approach to the North Atlantic requires three modifications in the Environment Structure and TC-Environment transformation mechanisms: (i) A Low Synoptic Pattern is defined; (ii) a variation on the North-oriented Pattern is added; and (iii) a Weak Westerlies Synoptic Region is defined in the Standard Pattern. Subtropical Ridge Modification is found to be the most important transformation mechanism. A preliminary climatology of Synoptic Patterns, Regions, Pattern/Regions, and transitions is developed. While the Standard Pattern is the most common, it is surprising that the Weakened Ridge Region is so prevalent. Storm tracks in each Pattern/Region combination reveal a characteristic track motion for each Pattern/Region.

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SYSTEMATIC AND INTEGRATED APPROACH TO TROPICAL CYCLONE TRACK FORECASTING IN THE NORTH ATLANTIC

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I. INTRODUCTION

A. TROPICAL CYCLONE TRACK FORECASTING

The accurate forecasting of tropical cyclone (TC) movement is important for a large portion of the world. Tropical meteorologists at centers throughout the world are continually striving to reduce their forecast errors of tropical cyclone movement. Major decisions are based on the forecast movement of tropical cyclones. A mistake in the forecast movement of a tropical cyclone can endanger lives, ships, businesses, and homes. The Joint Typhoon Warning Center (JTWC) in Guam is responsible for forecasting tropical cyclones in the North Pacific. The National Hurricane Center (NHC) in Miami, Florida has the responsibility for the North Atlantic and eastern North Pacific to 140°W.

Many problems exist in the forecasting of tropical cyclones. A large problem is the lack of observations throughout most of the tropical oceans. To combat this, forecasters use objective aids and numerical weather prediction models to help them in their forecasts. The numerical weather prediction models are viewed as the most likely tool to provide an integrated TC track and structure forecast, and thus lead to an advancement in TC forecasting. However, these models have systematic errors in TC track forecasts. The knowledge that forecasters acquire through experience is another invaluable tool. The combination of numerical guidance, objective aids, and experience-gained knowledge is often expressed in terms of thumb-rules. These thumb-rules and their application can vary greatly between warning centers. This variation in application can be large even between individual forecasters. Consequently, the temporal consistency

of the official forecasts may be degraded, and may not improve upon objective forecasts as expected (Elsberry and Dobos 1990).

Carr and Elsberry (1994; hereafter CE) believe the principle weaknesses in TC forecasting are:

- insufficiently integrated and balanced treatment of the track, intensity, and wind distribution sub-problems;
- an environment-driven perspective that does not sufficiently account for significant interaction of the TC with its environment;
- excessive reliance on empirical techniques and thinking so that dynamical reasoning is underemphasized; and
- an insufficiently systematic and standardized approach, which results in degradation of forecast temporal consistency.

Using these weaknesses as motivation, CE proposed a new systematic and integrated approach to tropical cyclone track forecasting (abbreviated title of Systematic Approach).

The Systematic Approach was developed to help forecasters more insightfully and consistently: (i) interpret the TC motion characteristics based on evolving global model fields; and (ii) anticipate errors in the TC forecast tracks provided by the global model and by other objective track forecast aids that depend on the numerical model (Carr et al. 1995). CE contains an extensive description of the meteorological knowledge base utilized. The Systematic Approach was designed around the procedures and techniques of JTWC in Guam and the analyses and forecasts of the U. S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, CA.

The Systematic Approach to TC track forecasting is organized into three phases: Numerical Guidance Analysis, Objective Techniques Analysis, and Official Forecast Development (Fig. 1). Each of these phases is further divided into resources, knowledge bases, and process components. CE provides details on these specific components.

The remainder of this Chapter reviews the Numerical Guidance Analysis phase. The knowledge base of the Numerical Guidance is the TC-Environmental conceptual models proposed by CE. The conceptual models developed in the Systematic Approach characterize the Environment Structure, the TC Structure, and the TC-Environment transitions.

B. ENVIRONMENT STRUCTURE

The Environment Structure is defined by CE in terms of Synoptic Patterns and Synoptic Regions. The Synoptic Patterns are the large-scale circulation features including adjacent cyclones and anticyclones. CE identify four Synoptic Patterns in the western North Pacific basin (Fig. 2). Within the four Synoptic Patterns are six Synoptic Regions (Fig. 2) that are associated with a particular environmental steering that is imposed on the TC. The following is a brief explanation of each Synoptic Pattern and Region (see CE for in-depth descriptions).

1. Synoptic Patterns

The Synoptic Patterns are conceptual models based on the Navy Operational Global Atmospheric Prediction System (NOGAPS) streamline and isotach analyses primarily at 500 mb. The structure and orientation of the mid-tropospheric subtropical ridge is the prominent feature in many of the conceptual models. The four Synoptic

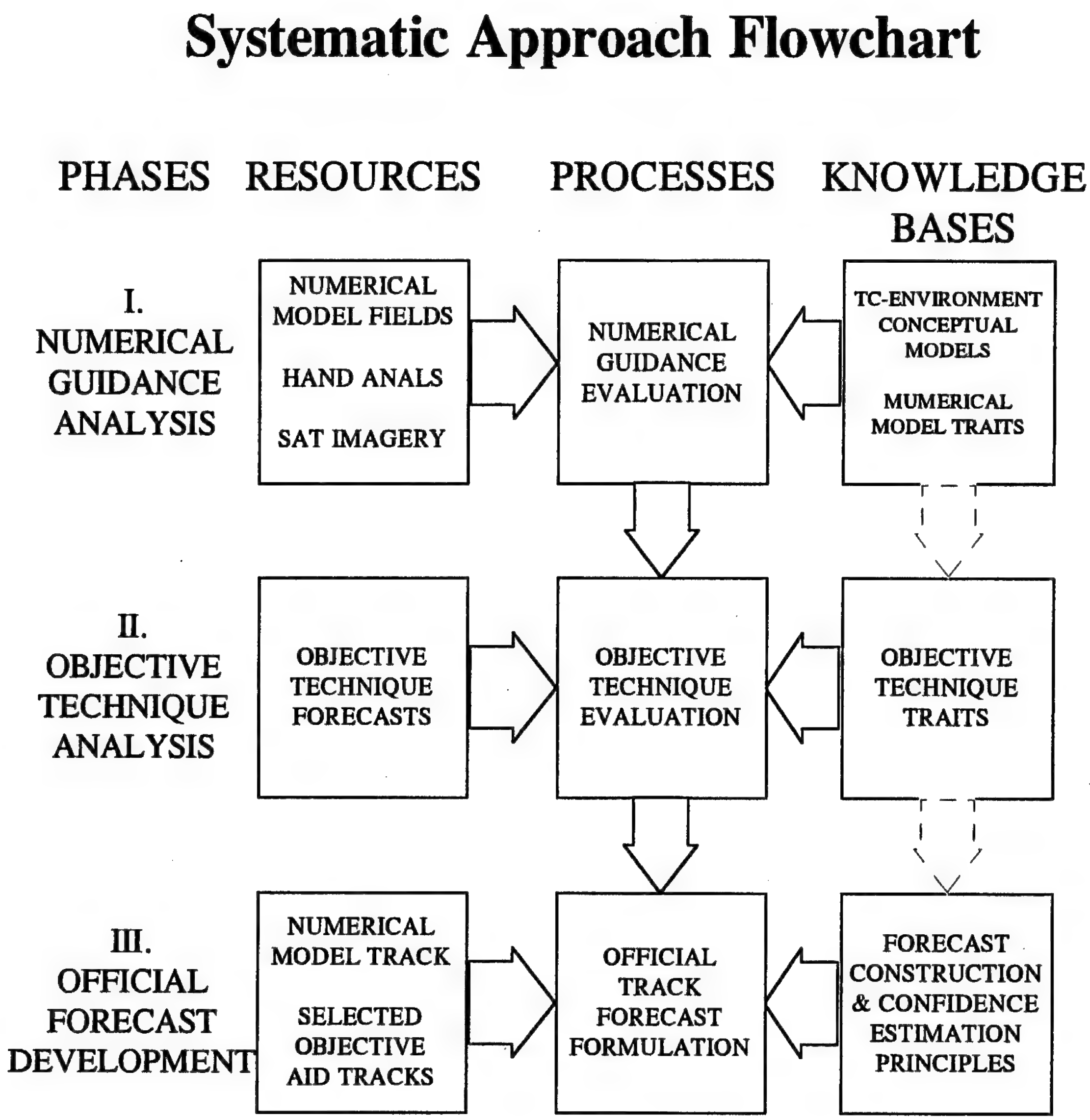

Figure 1. Schematic flow chart of the three phases (left side) and components (top) in the systematic and integrated approach to TC track forecasting (from Carr and Elsberry 1994).

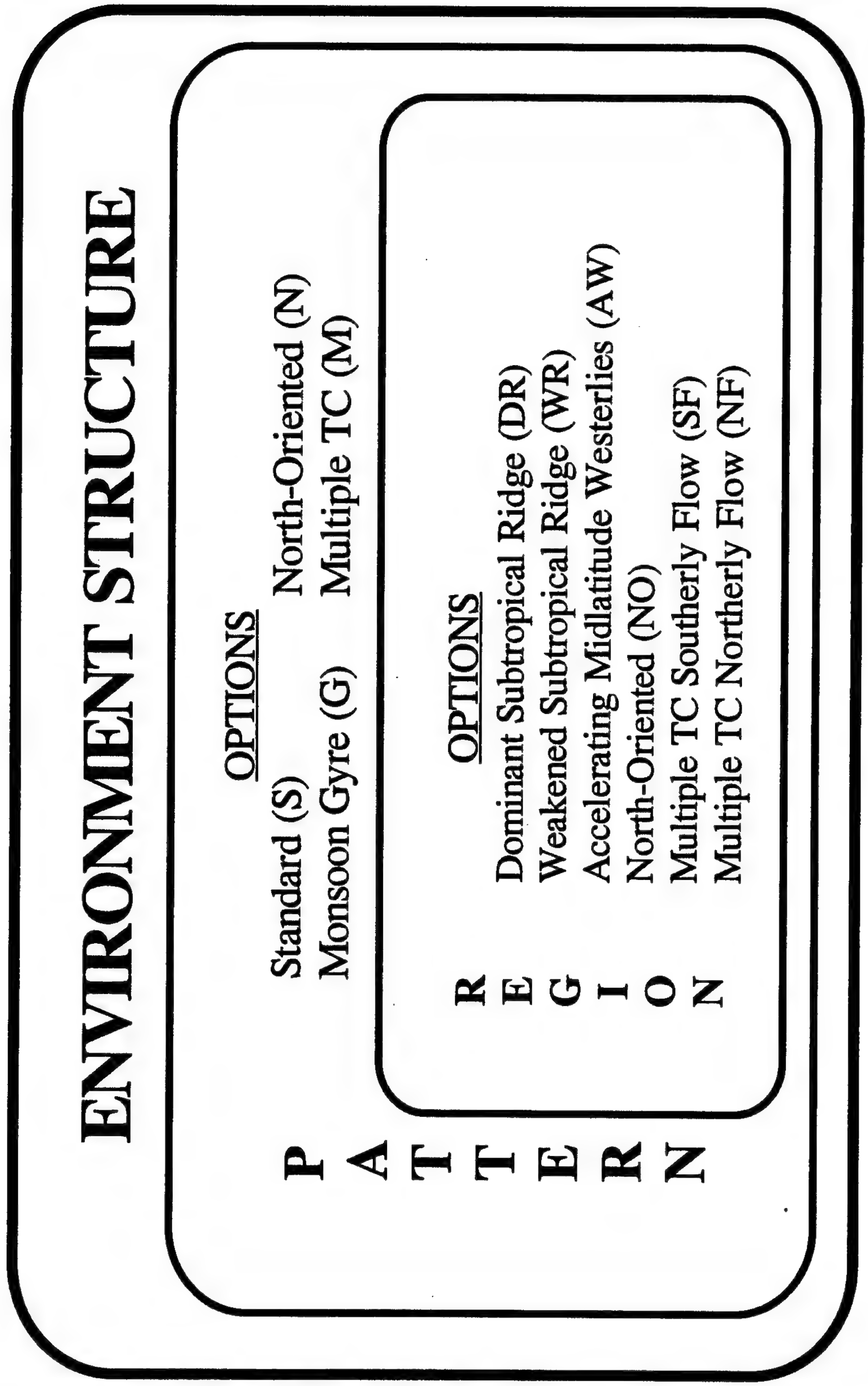

Figure 2. Environmental Structure for the western North Pacific tropical basin comprised of Synoptic Patterns and further subdivided into Synoptic Regions (from Carr et al. 1995).

Patterns are Standard (S), North-Oriented (N), Monsoon Gyre (G), and Multiple (M) Tropical Cyclone.

The S Synoptic Pattern is identified when the axis of the ridge circulation influencing the steering of the TC is approximately zonally-oriented. Ideally, the sub-tropical ridge separates the tradewind easterlies and the mid-latitude westerly flow. The ridge structure may be modulated by the passage of midlatitude troughs and ridges.

The conditions for classifying a Synoptic Pattern as N are: (i) a significant break in the subtropical ridge must be present poleward of the TC; and (ii) a prominent, and primarily north-south oriented, ridge exists to the east of the ridge break that also extends significantly equatorward of the latitude of the TC.

Identifying the G Synoptic Pattern requires: (i) there is present in the vicinity of the TC a particular type of monsoonal circulation that will hereafter be termed a monsoon gyre (MG); and (ii) the TC has a position relative to the MG that its steering is directly influenced by the MG.

Multiple (M) Tropical Cyclone Synoptic Patterns are identified when two TCs are: (i) in proximity to each other (less than about 20° lat.), but with a separation distance that would not result in a significant binary interaction, which generally occurs at less than 10-12° lat. (Brand 1970; Dong and Neumann 1983); (ii) oriented approximately east-west; and (iii) sufficiently close (north or south) to the ridge axis that the height gradient between the western (eastern) TC and the eastern (western) ridge circulation subjects the eastern (western) TC to moderately strong (10-15 kt) and predominantly poleward

(equatorward) steering flow. However, it is possible for additional TCs to be in proximity without setting up competing M Synoptic Patterns.

2. Synoptic Regions

The Synoptic Regions are conceptual models to classify areas within the Synoptic Patterns that determine the environmental steering of the TC (Fig. 2). The Synoptic Regions are generally described in a specific orientation relative to ridge circulations with well-defined boundaries. A total of six Synoptic Regions are identified within the four Synoptic Patterns. Several of the regions are found in more than one pattern.

The Standard Synoptic Pattern is comprised of the Dominant Ridge (DR), Weakened Ridge (WR), and Accelerating Westerlies (AW) Synoptic Regions. The DR Region involves TC locations satisfying the following: (i) poleward of the monsoon or equatorial trough axis, or poleward of about 5° lat. if no trough exists; (ii) equatorward of the axis of an east-west oriented ridge circulation that tends to dominate the motion of the TC by producing roughly easterly steering of about 10-15 kt; and (iii) not in the vicinity of a "significant" break along the ridge axis that weakens the steering flow and makes it more southerly. The WR Region, which is unique to the S Pattern, consists of all locations that are: (i) equatorward of the subtropical ridge axis; (ii) east of the center of a break in the ridge; and (iii) close enough to the break to be in weak (5-8 kt), southeasterly-to-southerly steering. The AW Region within the S Synoptic Pattern consists of the locations that are: (i) poleward of the ridge axis, and generally within about 10° lat. of the ridge axis; and (ii) east of the ridge-break neutral point.

The N Synoptic Pattern only contains two Synoptic Regions, the North-oriented (NO) and the AW. The NO Synoptic Region consists of locations that are in a predominantly southerly flow to the west of the anomalous, meridionally-broad ridge circulation. The AW Synoptic Region of the N Synoptic Pattern is fundamentally the same as in the S Synoptic Pattern.

The G Synoptic Pattern contains three regions. The NO and AW Synoptic Regions are essentially the same as previously described for the N and S Patterns. The DR Region of the G Pattern is the region to the northwest of the MG where east-northeasterly steering occurs due to the gradient between the MG and the ridge to the north.

The M Pattern contains the Northerly Flow (NF) and Southerly Flow (SF) Regions that are symmetric about a north-south line running through the centroid between the TCs. The SF (NF) Region consists of locations that are: (i) in the predominantly southerly (northerly) environmental flow in the vicinity of the line running from the center of the western (eastern) TC to the center of the eastern (western) ridge circulation; and (ii) no closer than about 10° lat. to the western (eastern) TC.

C. TRANSITIONAL MECHANISMS

A transition involves a change from one Synoptic Pattern to another, or from one Synoptic Region to another Region within the same Pattern. The Environment Structure may be altered by either the TC or factors within the environment. On the one hand, TC-Environment transformations (Fig. 3) are changes to the Environment Structure that are the consequence of the TC(s). On the other hand, the environmental effects (Fig. 4) are

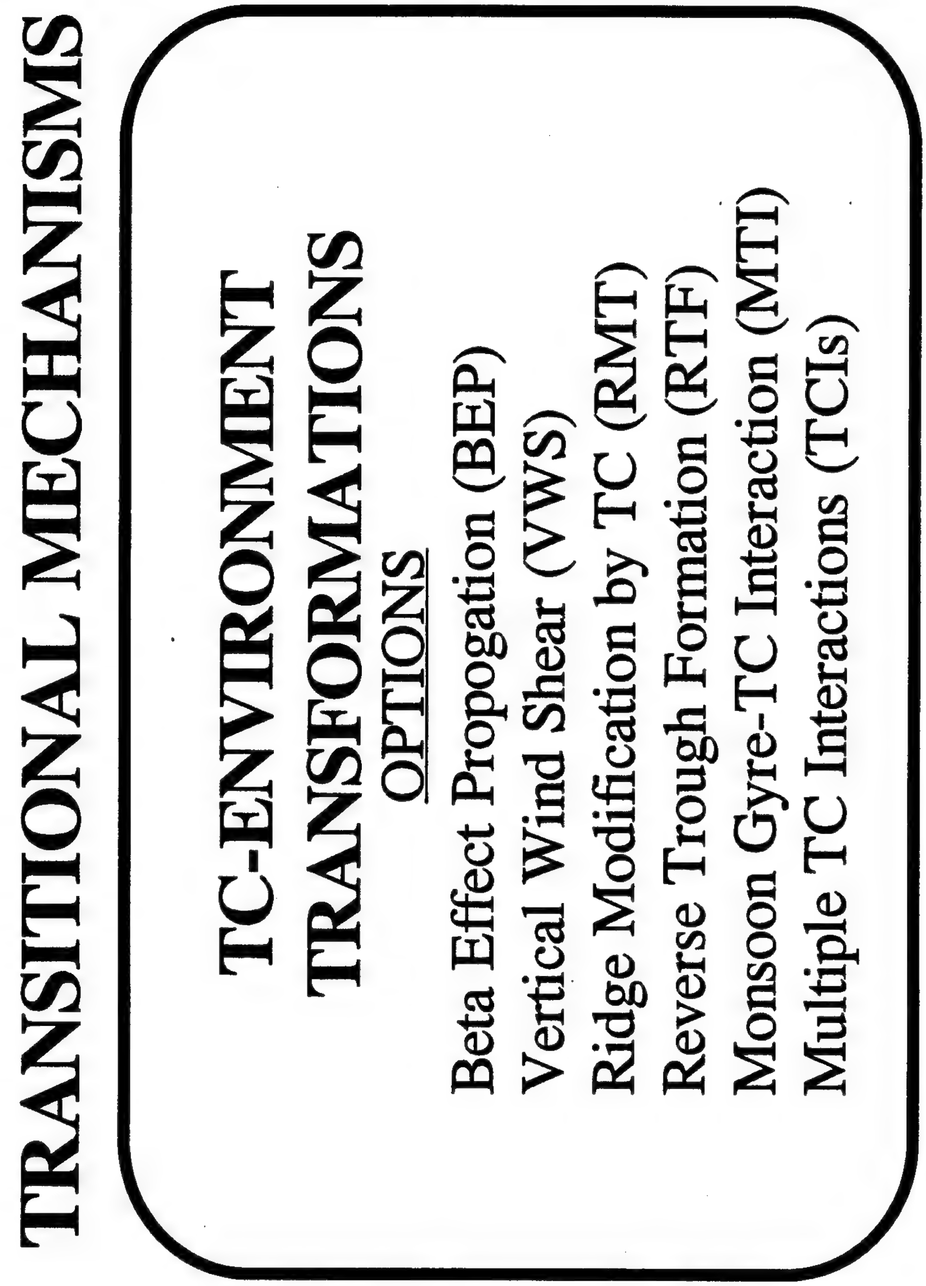

Figure 3. Transitional Mechanisms initiated by various combinations of Environment Structure and TC Structure creating the above identified Tc-Env. Transformations for the western North Pacific basin (from Carr et al. 1995).

TRANSITIONAL MECHANISMS

ENVIRONMENT EFFECTS

OPTIONS

Advection by Environment (ADV)
Monsoon Gyre Formation (MGF)
Monsoon Gyre Dissipation (MGD)
Subtropical Ridge Modulation (SRM)

Figure 4. Transitional Mechanisms initiated by factors within the environment (excluding the TCs) identified for the western North Pacific basin (from Carr et al. 1995).

changes to the Environment Structure that are caused by related factors of the environment that would exist even if the TC were not present.

D. METHODOLOGY

The determination of the Environment Structure utilizing operational analyses is the first goal in the Numerical Guidance Analysis phase. CE recommend varying the optimum steering level based on the TC intensity conceptual model. The Numerical Guidance analyses fields most readily available at the Naval Postgraduate School are at 500 mb. Thus, the 500 mb NOGAPS analyses from FNMOC are annotated with the warning and past 12-, 24-, and 36-h positions, translation speeds, and intensities (Fig 5.)

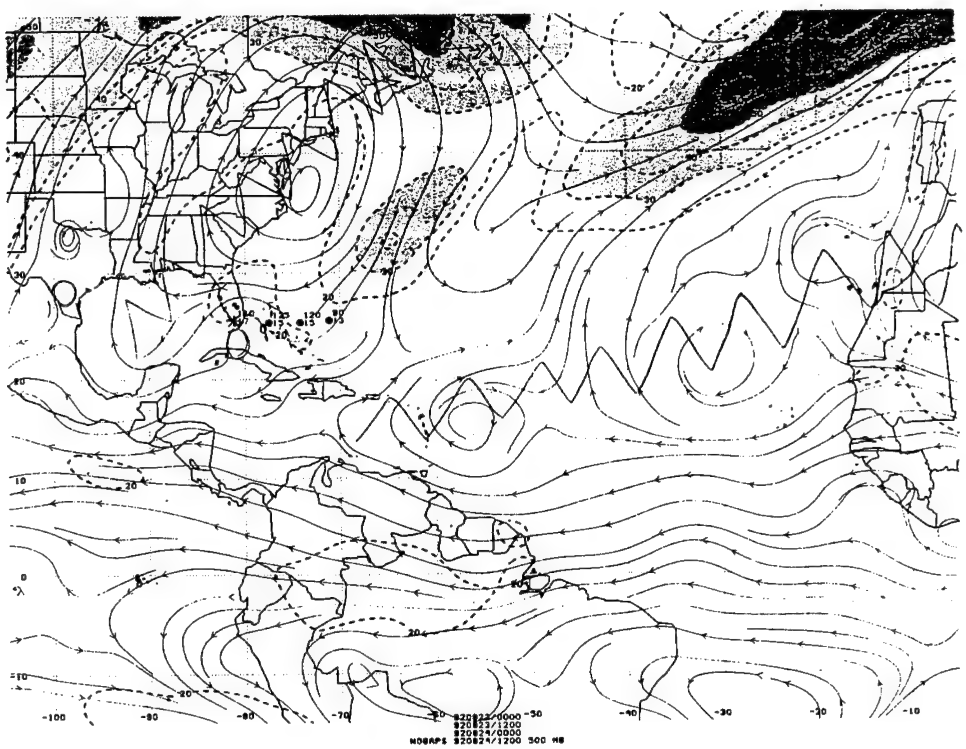

Figure 5. Example of a NOGAPS 500 mb streamline and isotach analysis with present (asterisk) and past 12-, 24-, and 36-h positions of Hurricane Andrew. Isotach contours are every 10 kt beginning with 20 kt, and regions exceeding 30 (50) kt have light (heavy) shading.

based on best track files from the appropriate forecast centers. Geostationary satellite infrared (IR) and visible (VIS) imagery were also utilized, when available.

E. PLAN OF THESIS

This thesis consists of two distinct parts. The author was trained in the Systematic Approach and then participated as one of three trainees in a reproducibility test, which was a "proof of concept" as applied to the western North Pacific for the 1989-93 seasons. This test will be summarized in the next Chapter (more detail is given in Carr et al. 1995). The second part of this thesis is the extension of the Numerical Guidance Phase to the North Atlantic tropical cyclones. Chapter III will describe this second part.

II. REPRODUCIBILITY TEST

A. INTRODUCTION

The Synoptic Patterns and Regions developed in the Systematic Approach of Carr and Elsberry (1994; hereafter CE) were the focus of this reproducibility test. The primary goal of conducting the reproducibility test was to ascertain whether trainees could determine the correct Synoptic Patterns/Regions, because correct identifications of these Patterns/Regions are an essential step in the application of the Systematic Approach. Another objective was that a study of the incorrect identifications by the trainees would highlight deficiencies in the descriptions of the Patterns/Regions or in the training phase of the program. That is, trainee misconceptions, difficulty in identifying Patterns/Regions, and misclassifications based on the conceptual models were anticipated, and do not necessarily indicate the knowledge base of the Systematic Approach was flawed. Rather, it may simply indicate deficiencies in the descriptions of the conceptual model(s), or in the training phase.

B. TRAINING

The three trainees had no previous tropical cyclone forecast experience. Their instruction in the Systematic Approach was to first read a draft version of CE. After each assigned reading, discussions were conducted to ensure the trainees possessed a thorough understanding of the material. Feedback and questions from the trainees contributed to improvements in the descriptions in the final version of the Carr and Elsberry technical report.

The second phase of the training began with some relatively easy storms from 1989, and the trainees were allowed to work together to apply the conceptual models of the Systematic Approach. Upon completion, a detailed debrief was conducted with the instructor that reinforced the principles. The trainees then moved on to another set of 1989 cases where they worked independently. This second set of cases was to establish whether the trainees were adequately trained to proceed with the reproducibility test. Again, an extensive debrief was conducted to intercompare the Pattern/Region assignments, and where differences existed, to review each individual's reasoning. After this second set of cases was completed, a determination was made to proceed to the actual reproducibility test.

C. REPRODUCIBILITY TEST

1. Synoptic Pattern/Region Combinations

This test documents the trainees' ability to identify correctly the Synoptic Pattern/Region combinations. Recognition of these Patterns/Regions constitutes the backbone of the Systematic Approach in producing an improvement over present TC track forecast techniques.

The percent correct identifications of each trainee (A-C) for a four-year (1990-1993) total for each of the ten possible Synoptic Pattern/Region combinations is shown in Table 1. Notice the overall combined correct percent identifications for the trainees was 77.5% for the Synoptic Patterns/Regions. This ability of trainees without previous TC forecasting experience to recognize these Patterns/Regions reinforces the validity of

Table 1. Percent correct identifications for each trainee (A-C) for the four-year (1990-1993) total for each of the ten Synoptic Pattern/Region combinations. The right column lists each trainee's overall percent correct identifications. The combined row shows percent correct for all three trainees combined. Below this row is the combined number of Pattern/Region combinations found in the four-year sample. In parentheses is the frequency of each Pattern/Region combination for the four years (from Carr et al. 1995).

		S/DR	S/WR	S/AW	N/NO	N/AW
TRAINEES	**A**	93.3	64.1	51.7	83.2	74.2
	B	94.7	16.7	8.8	70.8	71.3
	C	93.0	78.8	47.4	40.6	22.2
	Combined	93.6	53.3	35.6	65.0	56.7
		773	36	25.5	289.5	115.5
		(54.0)	(2.5)	(1.8)	(20.2)	(8.0)

		G/NO	G/DR	G/AW	M/NF	M/SF	OVERALL
TRAINEES	**A**	69.9	44.4	25.0	82.6	75.0	84.6
	B	29.3	35.5	23.8	25.0	59.1	76.9
	C	42.4	27.6	40.0	82.6	79.3	71.2
	Combined	47.8	34.4	29.5	66.7	72.0	77.5
		91.5	29.5	23.0	23.0	27.5	1434
		(6.5)	(2.0)	(1.6)	(1.6)	(1.9)	

the Systematic Approach. The test is important to the application of the Systematic Approach because this component involves subjective thought processes in the recognition and assignment of the Synoptic Pattern/Region combinations.

2. Synoptic Pattern/Region Transitions

a. Transitions

Whereas properly identifying the correct Synoptic Pattern and Region is important, of even greater importance is the proper recognition of when a cyclone transitions from one Synoptic Pattern/Region combination to another. Because such transitions will normally lead to significant changes in the track of the cyclone, recognition of an upcoming transition and the timing of that transition are tantamount to accurate track forecasts. It is in this area of reducing potential forecast errors associated with changing storm motion that the Systematic Approach can be most useful in its application. The hypothesis of CE is that a properly equipped forecaster can anticipate the Synoptic Pattern/Region transition and select (reject) the objective aid guidance that agrees (disagrees) with the anticipated transition (CE).

The scoring results are summarized in Table 2 by individual year and a 4-y combined total. The numbers of transitions in 1990 through 1993 are 15, 34, 60, and 32, respectively. The tables have a combined total of 423 transitions since each of the three trainees should have detected 141 transitions. That is, the combined sums for the individual years will be 45, 102, 180, and 96, respectively. Unless otherwise identified, all future references to the number of transitions for the individual years and combined 4-y total will be the total for all three trainees.

Table 2. Combined numbers of transitions that should have been detected by the three trainees, with separation into correct, similar, missed, false and flip-flops for each year and the 4-y combined total.

Year (Transitions)	Correct	Similar	Combined	Missed	False	Flip-flop
1990 (45)	28	13	41	4	3	9
1991 (102)	42	40	82	20	12	17
1992 (180)	92	52	144	36	6	24
1993 (96)	42	33	75	21	5	14
Combined (423)	204 (48.2%)	138 (32.6%)	342 (80.9%)	81 (19.1%)	26 (6.1%)	64 (15.1%)

b. Timing

Another important result is the trainee's timing of the transition. While identifying that a transition is occurring is extremely important, correctly timing the transition is also of importance. Helping the forecaster properly identify the timing of the transition is a goal of the Systematic Approach training.

A histogram of the 342 correctly and similarly identified transitions for the three trainees for the 4-y combined data set is given in Fig. 6. These correct or similar transitions were identified "on time" in 118 cases. However, one transition was identified 120 h late. Of the 342 correct/similar transitions, 245 (71.6%) were identified either 12 h late, on time, or 12 h early. These 245 well-timed transitions represent 58% of the 423 transitions that occurred in the 4-y combined data set. The transition timing distribution for the trainees is slightly shifted toward the late identifications. This is

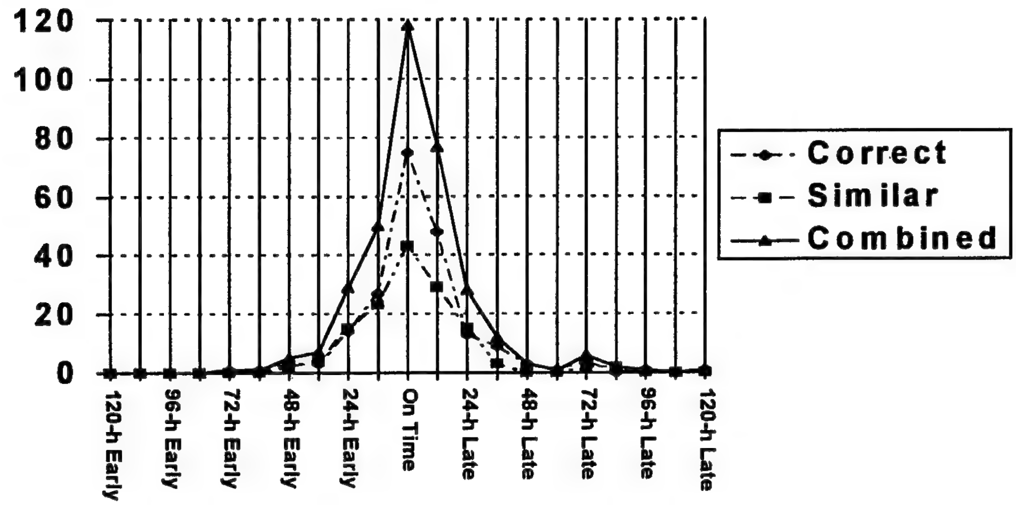

Figure 6. Histogram of timing of correct and similar transitions identified by the three trainees for the 4-y combined data set (from Carr et al. 1995).

understandable considering the trainees did not have the opportunity of looking backward and correcting for a missed transition.

If the "acceptable" timing windows for transitions is expanded to ±24 h, the number of correct/similar transitions is 302. This expanded window would result in 71.4% of the 423 transitions being identified as correct/similar transitions.

D. REVISIONS

The training for this reproducibility test of recognizing the TC-Environment situation occurred as the CE report on the Systematic Approach was being finalized. The proposed enhancements to be made to the training are based on the lessons learned during the reproducibility test. Two sources were utilized to apply the principles of the Systematic Approach to the TC-Environment situation. The first of these were the FNMOC NOGAPS analyses with the past tracks superposed (Fig. 5). The second was

the geostationary satellite infrared imagery that was utilized both as a validation of the features in the numerical analyses and to provide additional information on the TC-Environment situation.

The Gyre (G) Pattern definitions and the associated Regions as explained in CE were not applied well in this reproducibility test (see Table 1). The trainees' frequency of detection of the G Pattern was only 46.0%. A better or more consistent use of satellite imagery in detection of the G Pattern was the major impetus for this revised training section. The importance of utilizing the geostationary satellite imagery in conjunction with the NOGAPS analyses in validating "large-scale" synoptic features cannot be over-emphasized. CE state one premise of the Systematic Approach is to introduce the element of human reasoning based on a dynamic, meteorological knowledge base so that the numerical guidance is not the only source of information to the forecaster. The geostationary satellite imagery allows forecasters to develop a conceptual model independent of the numerical analyses. A subtle point in the Systematic Approach is the forecasters' ability to separate the individual effects of the TC from the environment and vice versa. In other words, a forecaster must be able to envision the synoptic environment without the TC present. As with the other Synoptic Pattern conceptual models, the forecaster must recognize that actual G Patterns depicted in NOGAPS analyses may vary from the idealized schematics found in CE.

A more consistent use of the geostationary satellite imagery in conjunction with the NOGAPS analyses should allow the forecaster to assign the correct TC-Environment

Structure. The deficiencies revealed by the reproducibility test emphasizes the importance of utilizing concurrently these sources of information.

E. SUMMARY

The original technical report of CE was based heavily on the operational TC forecasting experience of Carr during the 1990 and 1991 western North Pacific seasons. The reproducibility test performed two tasks. First, the validity of the Systematic Approach was reinforced by the success of the three trainees in recognizing the Patterns/Regions. While the comprehensive evaluation of many years of daily analyses exposed some problems and ambiguities in the Systematic Approach descriptions and in the trainees training, the consensus of the trainees and developers is that the TC-Environment conceptual models are sufficient to characterize nearly all of the variations of TC-Environment Structure that occur in the western North Pacific basin. Refinements of the Systematic Approach have been made (Carr et al. 1995) based on the reproducibility test, and the updated Environmental Structure framework of the Systematic Approach is summarized in Figs 2-4 above..

The second output of the reproducibility test was the assistance of the trainees in creating a five-year climatology data set. The addition of a climatology data set to the meteorological knowledge basis and TC-Environment conceptual models in the Systematic Approach allow the creation of new rules of thumb to be used for TC track forecasting in the western North Pacific.

III. APPLICATION TO ATLANTIC

A. INTRODUCTION

The Systematic Approach of Carr and Elsberry (1994; hereafter CE) was developed for the western North Pacific. The TCs that develop in the western North Pacific and North Atlantic basins differ greatly in size, strength, and types of tracks followed. However, CE hypothesized that the meteorological framework of the Systematic Approach would be generally applicable to other tropical basins of the world. For this reason, the Environment Structure developed in CE was used as a starting point for analysis of the tropical North Atlantic Synoptic Patterns and Regions. Nevertheless, it was anticipated that differences would be found between the western North Pacific and North Atlantic, which would require the modification of the Synoptic Patterns and Regions developed in CE, as well as the introduction of new Synoptic Patterns and Regions.

Although a similar approach as in the reproducibility test (see Chapter II.B) was used, the full storm tracks were available and adjustments in Pattern/Region assignments were allowed to achieve the best possible characterization of the Synoptic Pattern/Region. The 500 mb NOGAPS streamline and isotach analyses were used because of accessibility are reasonably representative of deep-layer mean steering. For periods during which the TC movement did not appear to be consistent with 500 mb steering, the 700 mb fields were consulted. Unlike the western North Pacific, twice daily visible or infrared satellite

imagery was not readily available. Copies of satellite imagery for requested periods were kindly provided by the National Hurricane Center for this study.

A five-year data set consisting of the tropical seasons of 1990-94 for the North Atlantic were examined. The objectives of this examination were to: (i) investigate the applicability of the CE meteorological framework to the North Atlantic; (ii) identify and describe any new Synoptic Patterns, Regions, or TC-Environment transformations; and (iii) create a climatological data base consisting of the Synoptic Pattern/Region frequency of occurrence, associated TC tracks, and preferred paths of transition. The similarities between the western North Pacific and North Atlantic tropical basins will be discussed first. In Section C, a discussion of the differences between the two basins will lead to the proposal of new Synoptic Patterns and Regions in Section D. Climatological results and a summary for the North Atlantic will be presented in Section E.

B. SIMILARITIES WITH WESTERN NORTH PACIFIC

The four western North Pacific Synoptic Patterns are described in Chapter I.B.1. Three of these four Synoptic Patterns are found in the North Atlantic, although with some slight variations. The Patterns common to both basins are the Standard (S), North-oriented (N), and the Multiple (M) TC. Each of the six Synoptic Regions within these Synoptic Patterns was also identified in the North Atlantic climatological data base. The Dominant Ridge (DR), Weakened Ridge (WR), North-oriented (NO), Accelerating Westerlies (AW), Northerly Flow (NF), and Southerly Flow (SF) Synoptic Regions are all identified in their respective Synoptic Patterns during at least one TC in the North Atlantic.

The subtropical ridge in the western North Pacific appears to be consistently east-west oriented, as it is anchored over the eastern portion of the Asian continent. By contrast, the subtropical ridge in the North Atlantic fluctuates more in position and strength than in the western North Pacific. Nevertheless, the subtropical ridge is still the dominant mid-tropospheric feature. Transitory mid-latitude circulations contribute to weaknesses in the subtropical ridge that may allow a TC to turn north and move through the ridge. The TC may either complete the recurvature and track east of north, or continue on a westward to northward track if the passage of a mid-latitude circulation re-establishes the ridge to the north of the TC. In general, these transitory mid-latitude features have a greater impact on the subtropical ridge in the North Atlantic compared to the western North Pacific.

The most common Synoptic Pattern for both basins is the S Pattern, which accounts for an extremely large 75% of the North Atlantic's 680 date/time groups (DTGs), versus 58% of the western North Pacific's 2485 DTGs. The second most common Synoptic Pattern is the N Pattern, which accounts for 27% of the western North Pacific DTGs and only 19.6% of the North Atlantic. These two Synoptic Patterns characterize the Environment Structure for the vast majority of the North Atlantic and western North Pacific TCs.

The most common Synoptic Region for both the North Atlantic and western North Pacific is the DR Region. The 38.7% of cases in this Region for the North Atlantic is

less than the 54% in the western North Pacific because it is only found in one Synoptic Pattern in the Atlantic compared to two Patterns in the Pacific. Specifically, the second (G) Pattern in the western North Pacific does not exist in the North Atlantic. The percentage of cases in the AW Region for both basins is about the same with 12.4% in the North Atlantic and 14% in the western North Pacific. The final similarity in the Synoptic Regions is that the NF and SF are not very common. Each of these two Synoptic Regions was found in 0.9% of the DTGs in the North Atlantic and 2% of the DTGs in the western North Pacific. This is expected because of the strict requirements for the M Pattern, especially that the TCs must be located within about 20° of each other, which rarely occurs in the Atlantic.

C. DIFFERENCES FROM WESTERN NORTH PACIFIC

One of the major differences in the Atlantic is the importance of the Subtropical Ridge Modification (SRM) transformation mechanism, which describes the impact of the mid-latitude transitory waves on the subtropical ridge. The SRM conceptual model was one of the refinements to the Systematic Approach made by Carr et al. (1995). In the western North Pacific, the mid-latitude waves did not appear to be very strong and had little impact on the subtropical ridge. However, the mid-latitude troughs and ridges in the North Atlantic are one of the more important factors in forecasting the track of a TC. The North Atlantic mid-latitude waves appeared to be stronger and had a greater amplitude than their western North Pacific counterparts. Combined with the less persistent subtropical ridge that is not strongly anchored by the North American land mass, this leads to larger apparent breaks in the subtropical ridge.

Only three of the four western North Pacific Synoptic Patterns are found in the North Atlantic because the Monsoon Gyre (G) Pattern is not found. A somewhat similar type of circulation that is found in the North Atlantic has lead to the introduction of a new Synoptic Pattern called the Low (L) Pattern. The L Pattern and its associated Synoptic Regions will be described in detail in Section D.1 of this chapter.

Several cases that are similar in dynamics and appearance to the western North Pacific N Synoptic Pattern are found in the North Atlantic. However, the dominant N Pattern in the North Atlantic differs in its formation dynamics, which necessitated a variation called the Atlantic North-oriented Pattern. Discussion of the formation, dynamics, and appearance of this Pattern is presented in Section D.2 of this chapter.

A new Synoptic Region within the S Pattern was necessary to account for North Atlantic TCs leaving the WR Region that did not quickly transition to the AW Region as in the western North Pacific. Two possible explanations for the lack of a quick transition from the WR to AW Region are (i) tropical cyclones that break through the subtropical ridge in the North Atlantic tend to do so farther south from the strongest winds of the midlatitude westerlies than in the western North Pacific or (ii) the higher amplitude midlatitude troughs and ridges have weaker winds associated with them. Consequently, the Atlantic TCs often move in a northeastward direction at forward speeds less than 15 kt, which had not been described in the Systematic Approach based on western North Pacific cases. This new Synoptic Region in the North Atlantic S Pattern will be described in Section D.3 of this chapter.

D. NEW SYNOPTIC PATTERNS/REGIONS

Descriptions of a new Synoptic Pattern, variations on the N Synoptic Pattern, and a new Synoptic Region for use in the Systematic Approach applied to the North Atlantic basin are given in the following sections.

1. Low Synoptic Pattern

A new Synoptic Pattern proposed for the North Atlantic tropical cyclones is the Low (L) Synoptic Pattern. Because tropical cyclone formation within an upper low circulation is extremely rare in the western North Pacific, such a Synoptic Pattern was not part of the original Systematic Approach of Carr and Elsberry (1994), or in the five-year climatology of Carr et al. (1995). The L Synoptic Pattern forms from an upper-level low or cyclonic circulation that has sufficient strength to extend downward to the mid-levels, where it often penetrates into a mid-level ridge (Fig. 7). This results in a relatively large closed cyclonic circulation that is completely surrounded by the ridge. Upper- and mid-tropospheric low pressure systems occur quite frequently in the North Atlantic, even during the summer months. In this sample, they were typically located in the central to eastern portions of the basin and were normally north of 35°N. However, a L Synoptic Pattern may occur in other areas of the basin. Clearly one of the special circumstances of the Atlantic basin is the presence of sufficiently high sea-surface temperatures to form TCs so far north. In many situations, a so-called baroclinic TC development occurs at the trailing end of a frontal circulation stagnated over the warm water.

The persistence or strength of this Synoptic Pattern may be greatly aided or hindered by the mid-level transitory cyclones and anticyclones passing to the north. In

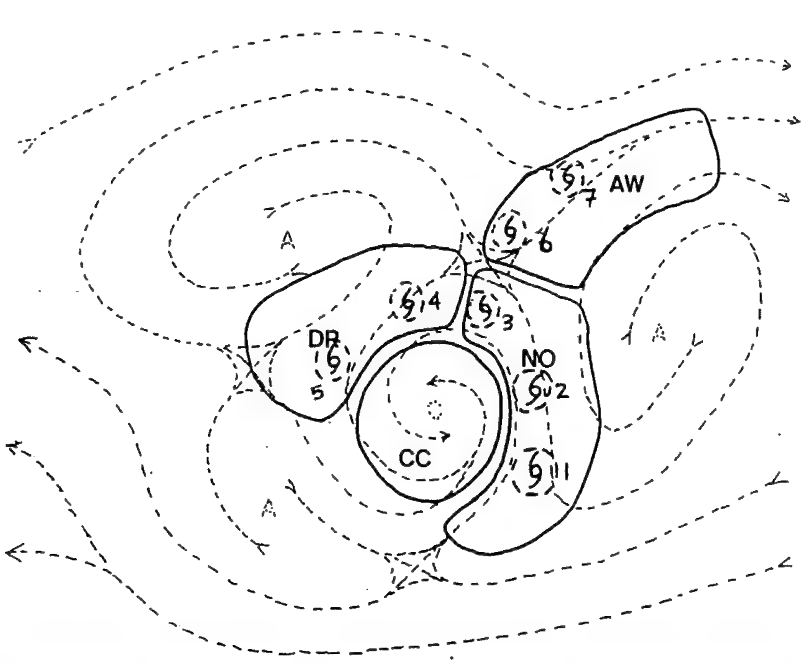

Figure 7. Schematic of the Low (L) Synoptic Pattern conceptual model. TC symbols and dotted concentric circles denote possible positions for TCs within the L Pattern.

the schematic (Fig. 7) of the 500 mb streamline analysis for the L Synoptic Pattern, the amplitude of the anticyclones surrounding the cyclonic circulation and embedded TC will also vary in response to transitory mid-latitude wave trains. These transitory waves may have a large impact on the continuation or termination of the L Pattern, which does not tend to persist very long unless a TC is identified at the center of the low. For these reasons, the forecaster must be aware that the L Pattern depicted in NOGAPS analyses will vary somewhat from the idealized schematic (Fig. 7) depending on the positions and amplitudes of mid-latitude features with respect to the cyclonic circulation.

The TC-Environment Structure will be classified as a L Synoptic Pattern whenever: (i) a TC is embedded in a cyclonic circulation that is significantly larger than the TC; and (ii) the TC has a position relative to the cyclonic circulation as suggested by

TC symbols 1-7 in Fig. 7; or (iii) a TC is identified at the center of the cyclonic circulation (Position 8).

While this L Synoptic Pattern appears similar to the Monsoon Gyre (G) Synoptic Pattern of the western North Pacific, the L Synoptic Pattern greatly differs in its formation, maintenance, and life cycle. In addition to being smaller in size and at a higher latitude than the monsoon gyre, the mid-troposphere cyclonic circulation is a downward reflection of a cold-core upper-tropospheric low, rather than an upward reflection of a warm-core monsoonal circulation. Thus, the amplitude and motion of the mid-troposphere cyclonic circulation in Fig. 7 will be determined to a large extent by the dynamics of the upper-tropospheric system. Such systems usually originate as cut-off lows that then drift west-southwest and dissipate in the subtropics or tropics. Formation of a warm-core TC within such a system will inject warm air into the cold low aloft, which should hasten the dissipation. As the amplitude of the upper-tropospheric low decreases, the induced cyclonic circulation at mid-tropospheric levels will also decrease.

The four Synoptic Regions associated with the L Synoptic Pattern are shown in Fig. 8. The Center of Circulation (CC) Region is not a true region as originally defined by CE in the Systematic Approach. When the entire cyclonic circulation is identified as the storm, this is identified as the CC Region. The pre-TC disturbance initially does not exhibit tropical characteristics while in this Region. As long as the pre-TC disturbance does not have tropical characteristics, it does not behave like a tropical system and is not steered by a deep-layer mean. While in this Synoptic Region, the pre-TC disturbance will tend to drift in a westerly or southwesterly direction, which is the typical direction upper-

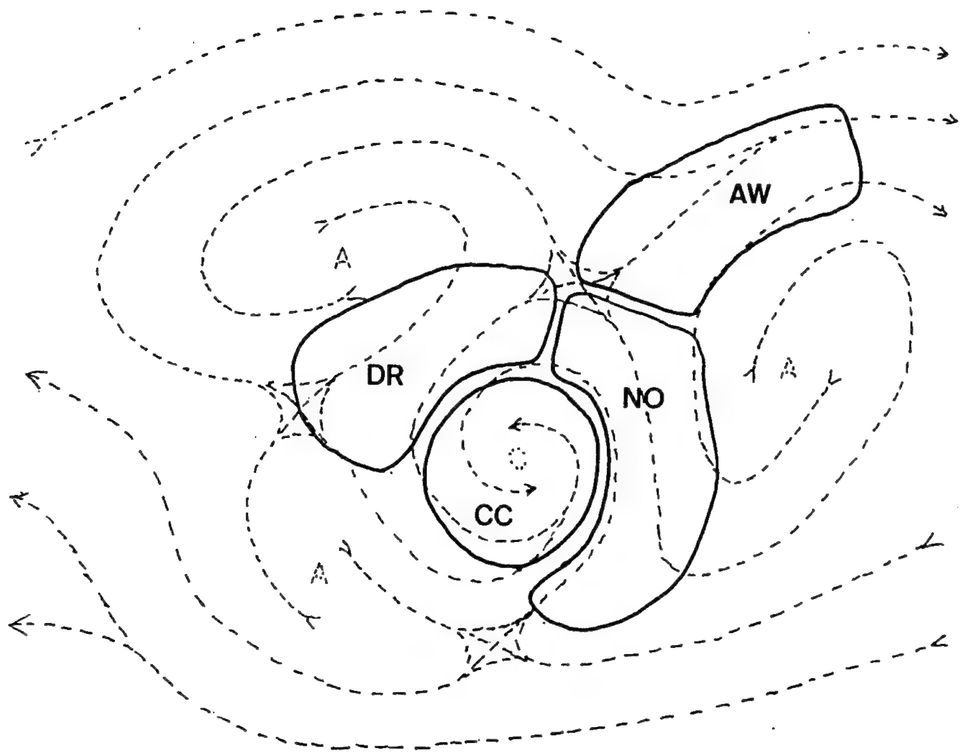

Figure 8. Schematic of the Low (L) Synoptic Pattern conceptual model, except with the boundaries of the associated Synoptic Region conceptual models added (solid lines).

tropospheric lows move. The North-Oriented (NO) Synoptic Region is fundamentally the same as in the N Pattern, although the western boundary of the NO Region in the L Pattern curves around the center of the cyclonic circulation. Although not actually observed in the five-year sample, a Dominant Ridge (DR) Synoptic Region is hypothetically possible in which the TC undergoes east-northeasterly steering primarily due to the gradient between the cyclonic circulation and the subtropical anticyclone cell to the north and northwest. In this sense, the L/DR Pattern/Region is analogous to the G/DR Pattern/Region in Fig. 2. Another possible, but not observed, Synoptic Region is the AW region, which occurs when the TC breaks through a weakness in the subtropical ridge to the north of the cyclonic circulation. Hurricane Josephine in 1990 in Fig. 9 came

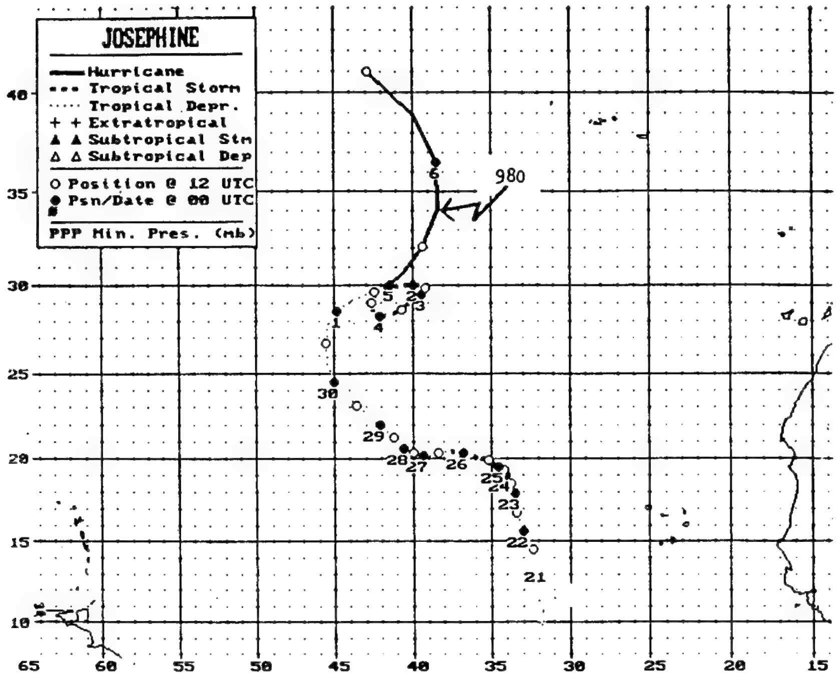

Figure 9. National Hurricane Center best track for Hurricane Josephine from 21 September to 6 October 1990 (from NHC 1990b).

close to breaking through the ridge and into the AW region, but Josephine lost tropical characteristics and was no longer tracked.

The inherent dissipative nature of cold lows, and consequently the short life span of the L Synoptic Pattern, are believed to be why the DR and AW Regions are not observed. In order for a TC to reach one of these Regions from the NO Region, the L Pattern would have to persist for 2-3 days while the TC moves around the cyclonic circulation. The observed life span of the L Pattern in this five-year sample is about 36-48 h, unless the TC is at the center of the circulation. When the pre-TC disturbance is in the CC Region, it usually takes 3-4 days before the cyclonic circulation begins to exhibit tropical characteristics.

Three scenarios are proposed for TC movement in relation to a L Synoptic Pattern. Two of the three scenarios pertain to advection around the cyclonic circulation in the pattern. The first scenario is different in that the TC forms as the entire non-tropical cyclonic circulation. In the early stages of the first scenario, the pre-TC disturbance does not have tropical characteristics and is usually considered a subtropical depression or cyclone. As long as the cyclonic circulation does not exhibit tropical characteristics, it will tend to drift to the west or southwest, which is typical for cut-off lows in the Atlantic. This scenario was observed in the cases of Tropical Storm Edouard and Hurricane Lili of 1990. Both TCs began as subtropical cyclones in the northern latitudes and their initial movement was westerly to southwesterly while the cyclonic circulation was not considered to have tropical characteristics. Once these storms developed sustained bands of convection characteristic of tropical disturbances, the larger scale cyclonic circulation began to dissipate, and the TC began to follow more closely the deep-layer mean or 500 mb synoptic steering flow.

Hurricane Lili of 1990 (Fig. 10) is a good example of a pre-TC disturbance in the CC Region. The pre-TC disturbance started on 6 October 1990 as a cold low aloft midway between Bermuda and the Azores. After penetration down to the surface, the TC acquired tropical characteristics 108 h after the initial report (NHC 1990a). The 500 mb NOGAPS streamline and isotach analyses (Fig. 11) for the early stages of Lili have a large cyclonic circulation with the TC identified at the center. As the pre-TC disturbance

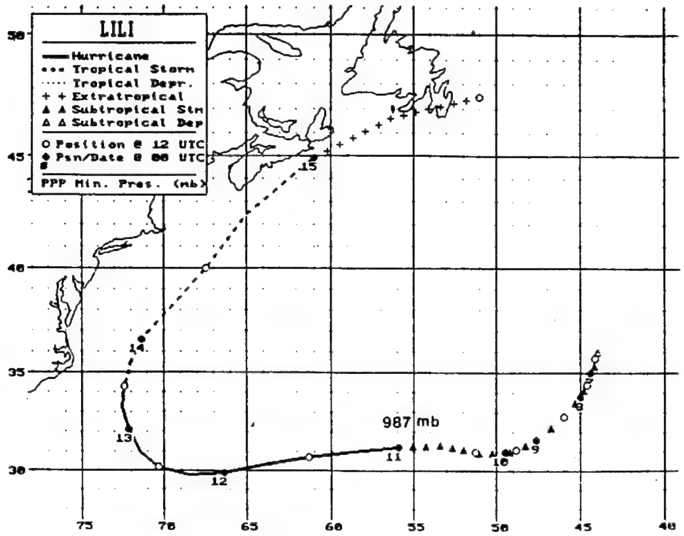

Figure 10. National Hurricane Center best track positions for Hurricane Lili during 6-15 October 1990 (from NHC 1990a).

was developing into Lili, the storm movement (Fig. 10) was to the southwest. After the system gained tropical characteristics, it then became Hurricane Lili on 0000 UTC 11 October. As the pre-TC disturbance was acquiring tropical characteristics, the storm translation slowed and changed direction during the period of 0000 UTC 9 October to 1200 UTC 10 October. After this time, the newly formed TC followed the deep-layer mean (500 mb) steering flow.

Two other scenarios for the movement of a TC in a L Pattern involve the translation around the outside of the larger scale cyclonic circulation. In the second scenario, a TC forms in the outer eastern portion of the cyclonic circulation and then moves with the southwesterly to southeasterly flow. If the cyclonic circulation does not drift to the southwest, the TC will have a counter-clockwise circular track, e.g., Hurricane Josephine during 1990 (Fig. 9). As Hurricane Josephine reached its last warning position

(Fig. 9) at the northern edge of the cyclonic circulation (Fig. 11a), a new tropical disturbance TD #13, which later developed into Hurricane Lili, was identified at the center of the cyclonic circulation. When the cyclonic circulation drifts to the southwest, a TC located on the eastern side would be initially in a southerly steering flow. Although the TC moves from the eastern side around to the north side, the track may be almost a straight line to the west, rather than the curved track one might expect from advection around a stationary cyclonic circulation.

The third scenario, which was not observed in the five-year sample, is that a TC may continue northward and recurve through a break in the ridge at the northern edge of the cyclonic circulation as indicated by positions 3, 6, and 7 in Fig. 8. For example, Hurricane Josephine in Fig. 9 and Fig. 11a is the only storm in the five-year sample to come close to completing the motion into the middle latitudes. As in the case of Josephine, the TC might also become an extratropical cyclone as it reaches the northern edge of the cyclonic circulation.

2. Atlantic North-Oriented Synoptic Pattern

Two North-oriented (N) Synoptic Patterns are identified in the North Atlantic tropical cyclone basin. The first is similar to the North-oriented Synoptic Pattern described by CE for the western North Pacific (CE 1994). According to CE, the conditions for classifying an environmental Synoptic Pattern as North-oriented (N) are: (i) a significant break in the ridge must be present poleward of the TC; and (ii) a prominent, and primarily north-south oriented, ridge to the east of the ridge break that also extends significantly equatorward of the latitude of the TC. This Synoptic Pattern

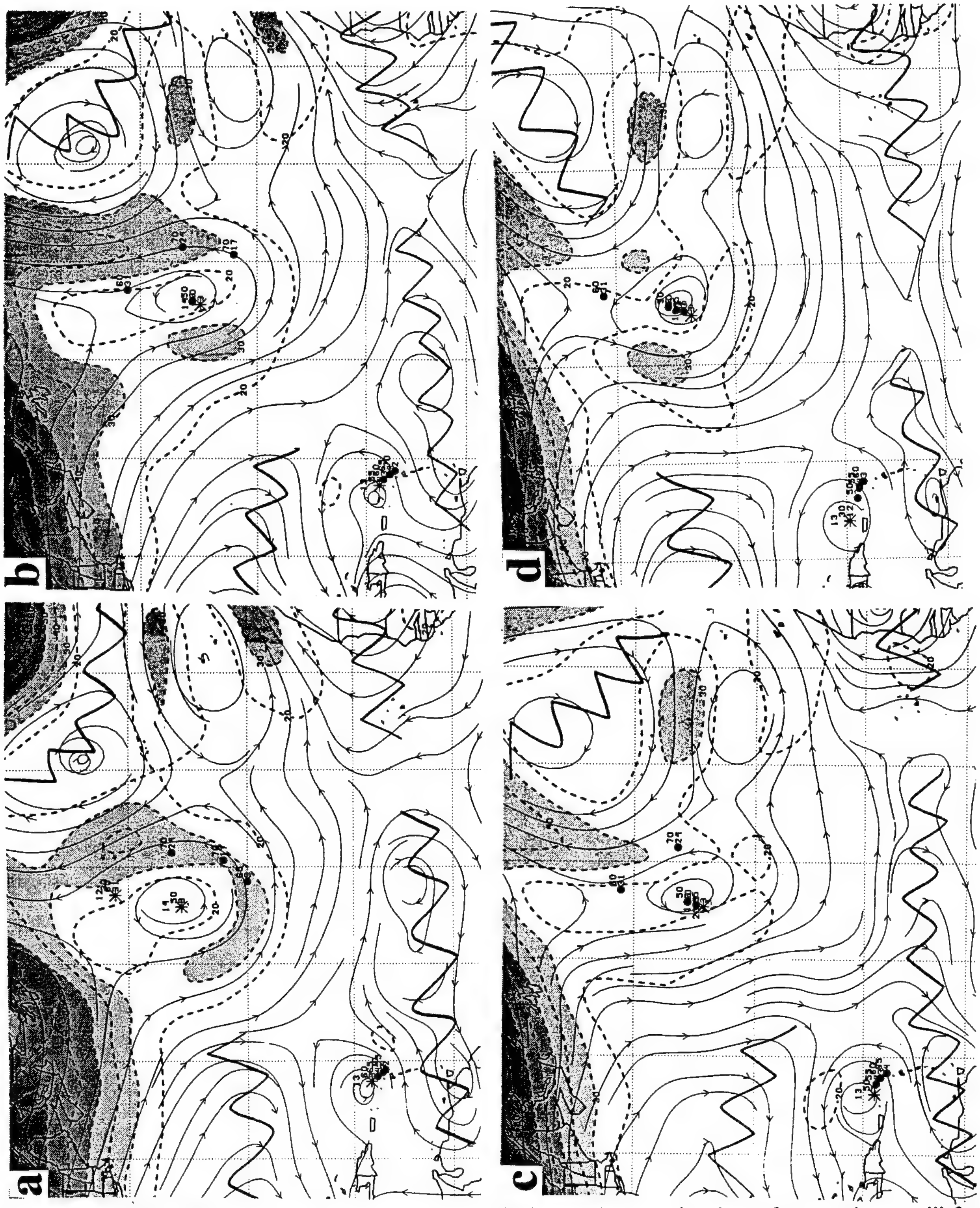

Figure 11. NOGAPS 500 mb streamline and isotach (kt) analyses as in Fig. 5 for Hurricane Lili for (a) 1200 UTC 6 October, (b) 0000 UTC 7 October, (c) 1200 UTC 7 October and (d) 0000 UTC 8 October 1990. Hurricane Lili is TC14 in the upper right portion of the domain.

is found to occur in the Atlantic several times in the five-year sample, normally at lower latitudes where mid-latitude waves do not have as great an impact. Figure 12 is a schematic of the N Pattern as described by CE.

A special Atlantic North-oriented Synoptic Pattern is defined because of differences from the one described by CE. The requirements for the Atlantic variation of the North-oriented Synoptic Pattern are: (i) a relatively strong, east-west oriented subtropical ridge equatorward of the TC; and (ii) the easterly portion of the ridge becomes elongated in the north-south direction in association with a passing mid-latitude ridge. The schematic (Fig. 13) of the Atlantic North-oriented Synoptic Pattern appears as an inversion of the Pacific North-oriented Synoptic Pattern of CE. However, the

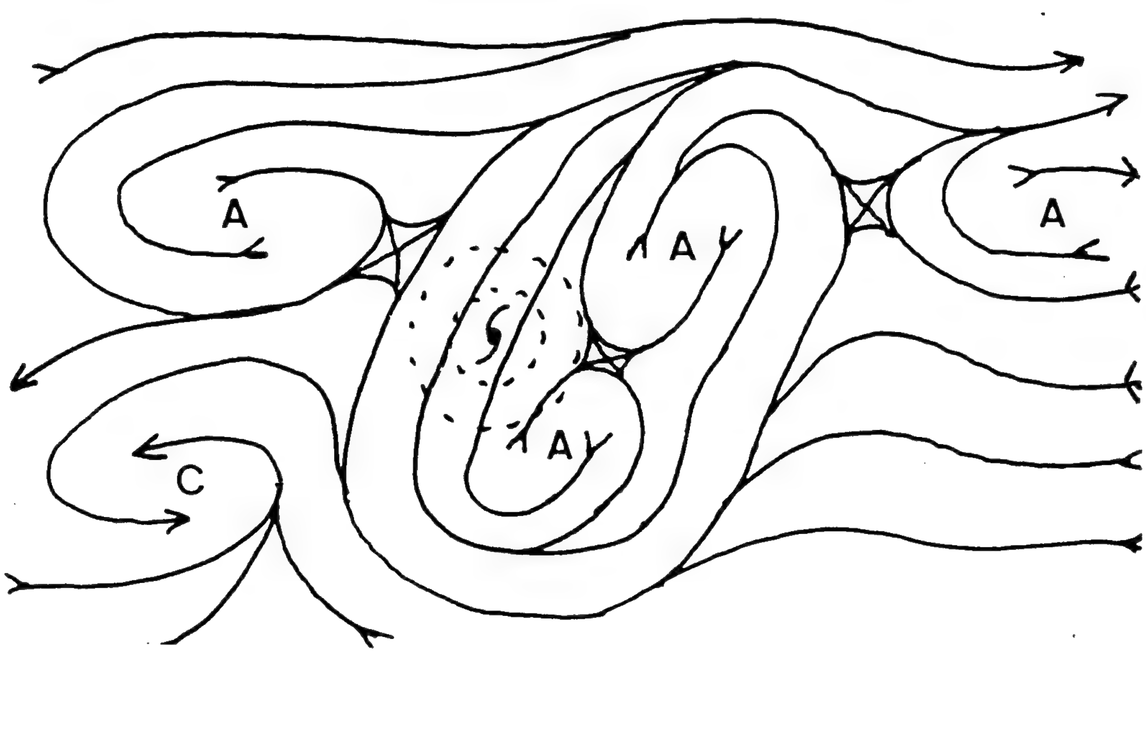

Figure 12. Schematic of the western North Pacific North-oriented (N) Pattern conceptual model. TC symbols and dotted concentric circles denote possible positions for TCs within the N Pattern (from CE 1994).

evolution during the Environment Structure transition to the Atlantic North-oriented Pattern is completely different between the two basins.

The dynamics associated with the development and maintenance of the North-oriented Synoptic Pattern of CE are not well understood. The pattern is intimately tied to the TC-Environment transformations called Ridge Modification by a large TC (RMT) and Monsoon Gyre-TC Interaction (MTI). Since monsoon gyres do not exist in the Atlantic, MTI is not discussed. The RMT is thought to be comprised of the following elements:

(i) Erosion of the subtropical ridge to the west and poleward of the large TC arising from β-induced positive relative vorticity advection;

(ii) Building of a significant peripheral ridge equatorward and to the east of the large TC owing to intense β-induced negative relative vorticity advection; and

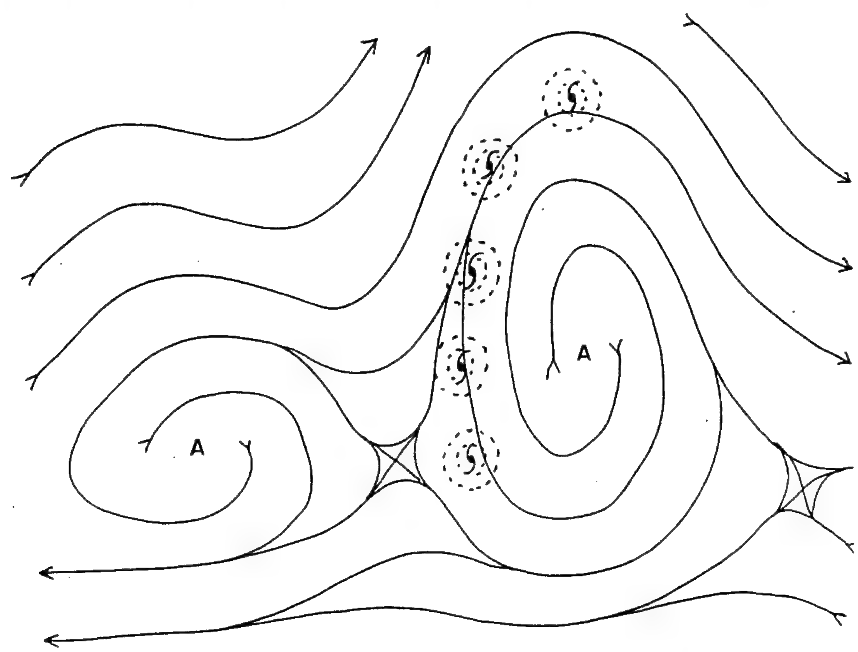

Figure 13. Schematic of the Atlantic North-oriented (N) Pattern conceptual model. TC symbols and dotted concentric circles denote possible positions for TCs within the N Pattern.

(iii) Concomitant weakening of the subtropical ridge poleward and to the east of the TC and amplification of the β-induced peripheral ridge owing to a barotropically unstable conversion from the subtropical ridge to the β-induced ridge, which tends to result in a single extensive ridge feature with northeast-southwest orientation that provides an additional southwesterly steering component to the TC.

The cases of RMT observed in the Atlantic are much weaker than in the Pacific. This may be due to a combination of the more cellular structure of the subtropical ridge and the generally smaller size of the Atlantic TCs.

The Atlantic North-oriented Synoptic Pattern is observed to have a very different mode of formation, which is here characterized by the Subtropical Ridge Modulation (SRM) conceptual model of Carr et al. (1995). The SRM transitional mechanism may account for transitions in the Environment Structure by either weakening or strengthening the subtropical ridge. The amplitude of the mid-latitude waves in this study of the Atlantic TCs appears to be greater than was observed in the reproducibility study in the Pacific (Chapter II.C). The Atlantic North-oriented transformation usually involves SRM in a process as follows:

(i) An approaching mid-latitude trough results in a break in the subtropical ridge to the north of the TC (Fig. 14a). The size of the break will depend on the strength of the mid-latitude trough. This scenario normally results in a transition from the Dominant Ridge (DR) Region in a Standard Pattern to a Weakened

Ridge (WR) Region. However, a transition from S/DR to N/NO may also occur if the mid-latitude trough is strong enough.

(ii) As the mid-latitude ridge immediately downstream of the trough passes the longitude of the TC, the ridge becomes superposed (with possible amplification) with the subtropical ridge circulation to the east of the TC. This superposition results in a north-south elongation of the subtropical ridge to the east of the break (Fig. 14b). The amplitude of the mid-latitude trough/ridge combination will determine the extent of the elongation. The timing of the mid-latitude trough passage will determine whether the TC will transition from the Weakened Ridge (WR), Weak Westerlies (WW), or Accelerating Westerlies (AW) Region to the NO Region of the Atlantic N Pattern.

(iii) The resultant motion of the TC will depend on the strength of the ridge building to the east of the break, and the tilt of the ridge will cause the motion of the TC to be between northwest clockwise to northeast.

The forecaster must be careful in assessing the possible influence of a mid-latitude trough, because not all troughs are strong enough to cause a significant break in the subtropical ridge. The forecaster must also forecast when the mid-latitude trough will be in the proper phase to cause such a transition. The meridional extent of the trough is the most important factor in determining if the trough will result in: (i) only a break in the subtropical ridge that leads to a transition from the DR Region to the WR or AW Regions while maintaining the S Pattern; or (ii) a break in the ridge and an elongation of the eastern portion of the subtropical ridge that leads to a Pattern/Region transition from S/DR

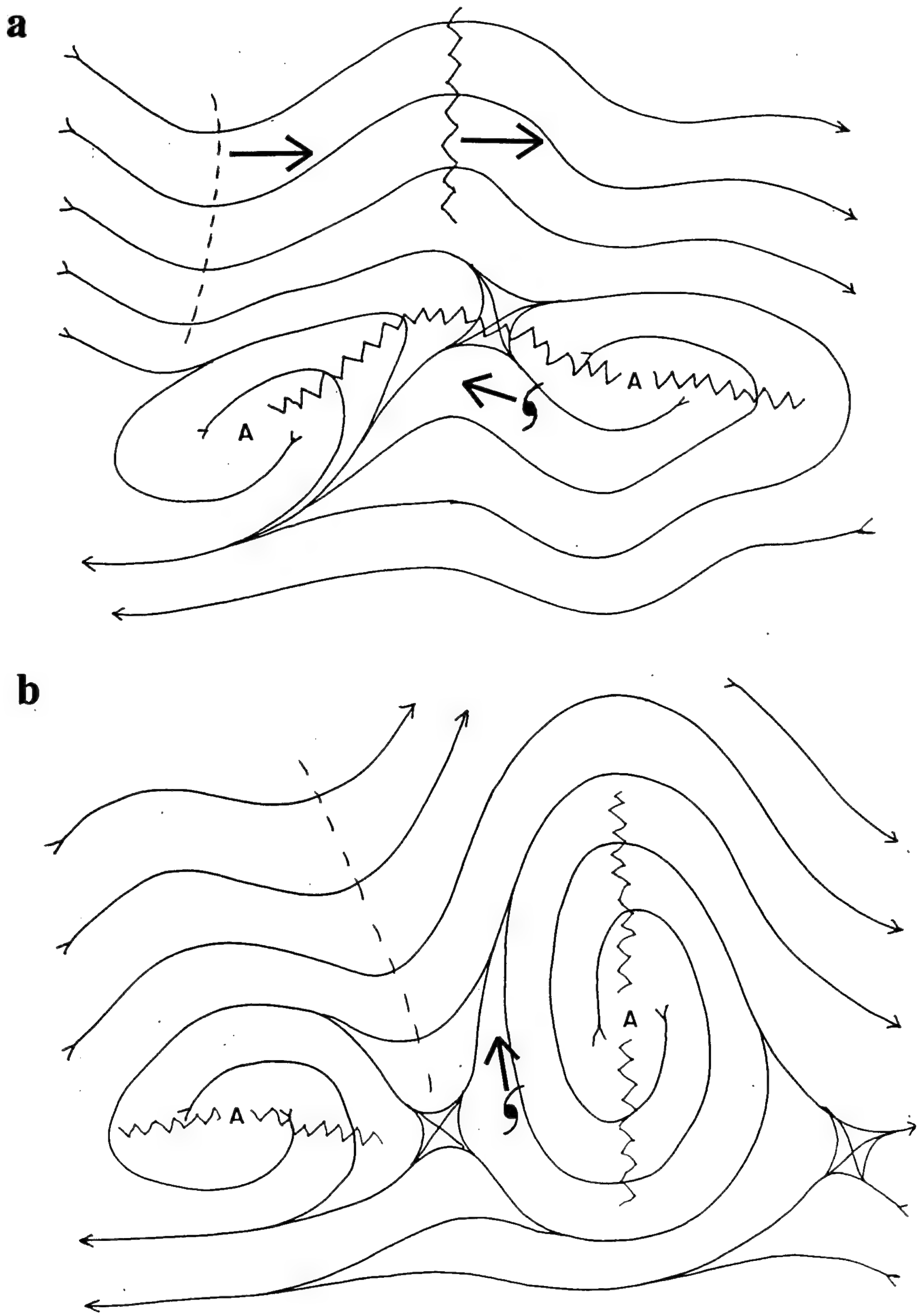

Figure 14. Schematic of the SRM transformation from a (a) S Pattern to a (b) Atlantic N Pattern.

to N/NO. The forecaster must also be aware that the mid-latitude trough/ridge system may continue to move eastward beyond the TC, which may result in a quick transition from the North-oriented Synoptic Pattern and back into the Standard Pattern.

The north-south oriented ridge of both the Atlantic and Pacific North-oriented Synoptic Patterns leads to only two Synoptic Regions existing within this Synoptic Pattern (Fig. 15). A TC must be in either the North-oriented (NO) or Accelerating Westerlies (AW) Synoptic Regions.

The NO Synoptic Region consists of locations that are in the predominantly southerly flow to the west of the anomalous, meridionally-broad ridge circulation. This is true for both the Atlantic and Pacific North-oriented Synoptic Patterns. In the Pacific N Synoptic Pattern, translation speeds are normally below 15 kt in this region. In the Atlantic, the storm may have a translation speed of greater than 15 kt if it is below the

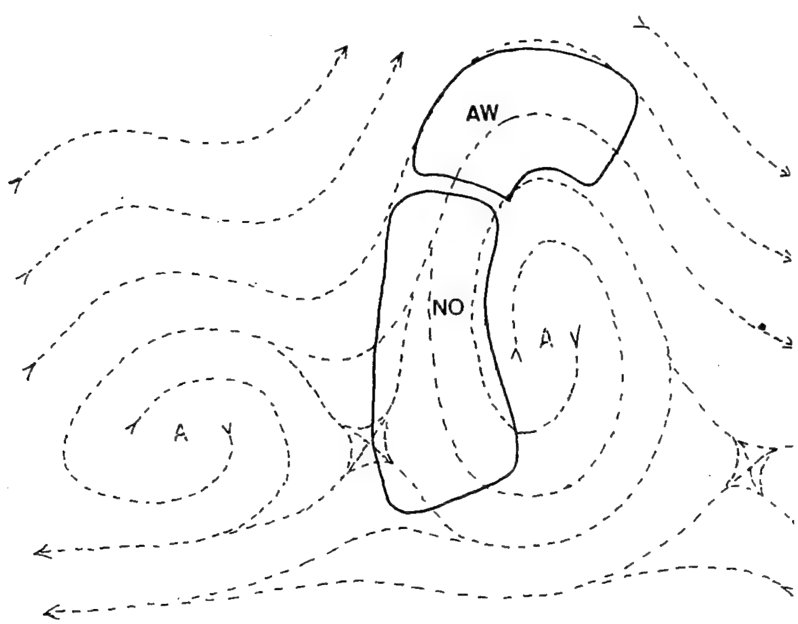

Figure 15. Schematic of the Atlantic N Synoptic Pattern, except with the boundaries of the associated Synoptic Region conceptual models added.

northernmost limit of the ridge axis to the east. Tracks within this Synoptic Region do not have to be straight as the Pattern is modulated by surrounding environmental features. In the Atlantic, the passing of mid-latitude troughs and ridges plays an enormously important role in this modulation.

The key factors in the AW Synoptic Region are the translation speed and location with respect to the ridge to the east. Although storm speeds in excess of 15 kt are required for a TC to be in the AW Region, speed is not the only determining factor. The second determining factor is where the TC is with relation to the axis of the ridge to the east. To be in the AW Region, the TC must be at or above the ridge axis, which will give the TC a northeasterly motion. Although numerous examples exist of TCs in the N Synoptic Pattern moving at greater than 15 kt in a northeasterly direction, these TCs are not considered to be in the AW Region because they are below the axis of the ridge.

3. Weak Westerlies Synoptic Region

A new Synoptic Region within the Standard Synoptic Pattern is defined as the Weak Westerly (WW) Synoptic Region (Fig. 16). The WW Synoptic Region is unique to the S Pattern. The WW Region may include the area outlined as the AW Region in Fig. 16. The difference between the two Regions is the translation speed of the TC. This region is mainly an Atlantic phenomenon because the storms do not move directly into the strong westerly mid-latitude flows as in the western North Pacific. The first characteristic of the WW Region is that the TC is moving slower than 15 kt. Two variations in the direction of TC movement are found within the WW Region. The first variation follows a transition out of the WR Region, which in the Pacific would

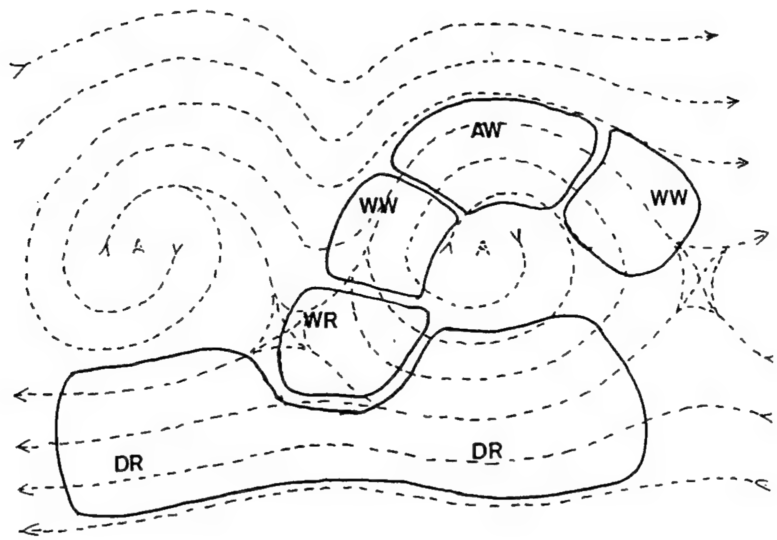

Figure 16. Schematic of the S Synoptic Pattern with the boundaries of the associated Synoptic Region conceptual models added.

immediately lead to the AW Region. After proceeding north of the ridge axis, a TC transitioning from the WR Region will move with a northeastward to eastward direction. The second variation in the direction for the WW Region comes after the storm has passed east of the subtropical ridge axis and begins to move in a southeastward direction on the east side of the ridge. This normally occurs if the TC recurves at a latitude well south of the strong westerly wind flow that occurs farther north in the North Atlantic. In both cases, the translation speeds of the TC should be less than 15 kt. The direction of the TC will depend on the position of the storm with respect to the subtropical ridge to its south.

E. CLIMATOLOGY OF SYNOPTIC PATTERNS AND REGIONS

1. Pattern and Region Frequencies

This preliminary (based on only five years) climatology of the Environment Structure characterizations is intended to give forecasters an idea of the frequency of these Synoptic Patterns and Regions. Table 3 is a list of the possible Pattern/Region combinations that characterize the Environment Structure in the Systematic Approach application to the North Atlantic. Each of 680 characterizations is counted as one occurrence of the particular Pattern/Region. For transitional situations with dual assignments, each Pattern/Region is counted as one half.

Table 3. Synoptic Pattern/Region combinations (including hypothetical combinations not observed) that characterize the Environment Structure in the Atlantic Systematic Approach.

Patterns	Regions
S - Standard	DR - Dominant Ridge WR - Weakened Ridge WW - Weak Westerlies AW - Accelerating Westerlies
N - North-oriented	NO - North-oriented AW - Accelerating Westerlies
L - Low	CC - Circulation Center NO - North-oriented DR - Dominant Ridge AW - Accelerating Westerlies
M - Multiple TCs	NF - Northerly Flow SF - Southerly Flow

a. Pattern Frequency

The frequency of TCs existing in each of the four Synoptic Patterns is shown in Fig. 17a. The Standard (S) Synoptic Pattern, which is characterized by a strong generally east-west oriented subtropical ridge with trade wind easterlies equatorward, is by far the most prevalent (74.9%) Pattern. This is much larger than the 58% of S Pattern characterizations in the western North Pacific, because many Atlantic storms may spend a large portion of their existence in a S/DR Pattern/Region combination. For example, TCs that form from African waves are equatorward of the subtropical ridge for long periods of time and thus are in a S Pattern.

When TCs are poleward of the subtropical ridge and in a North-oriented (N) Synoptic Pattern, the mid-latitude waves limit the length of time the Environment Structure can remain in the N Pattern. The N Synoptic Pattern, with a southerly environmental steering flow, exists in only 19.6% of the North Atlantic cases, which is down from the 27% of N Patterns in the western North Pacific.

The cases in which the TC is either under the influence of the Low (L) or Multiple (M) TC Patterns represent only 3.7% and 1.8%, respectively, of the 680 cases in the five-year sample. This is a much smaller percentage than the 15% combined total in the Monsoon Gyre (G) and M Patterns of the western North Pacific.

b. Region Frequency

The environmental steering is different depending on the Synoptic Region in which the TC is located. Each Synoptic Pattern has several associated Synoptic

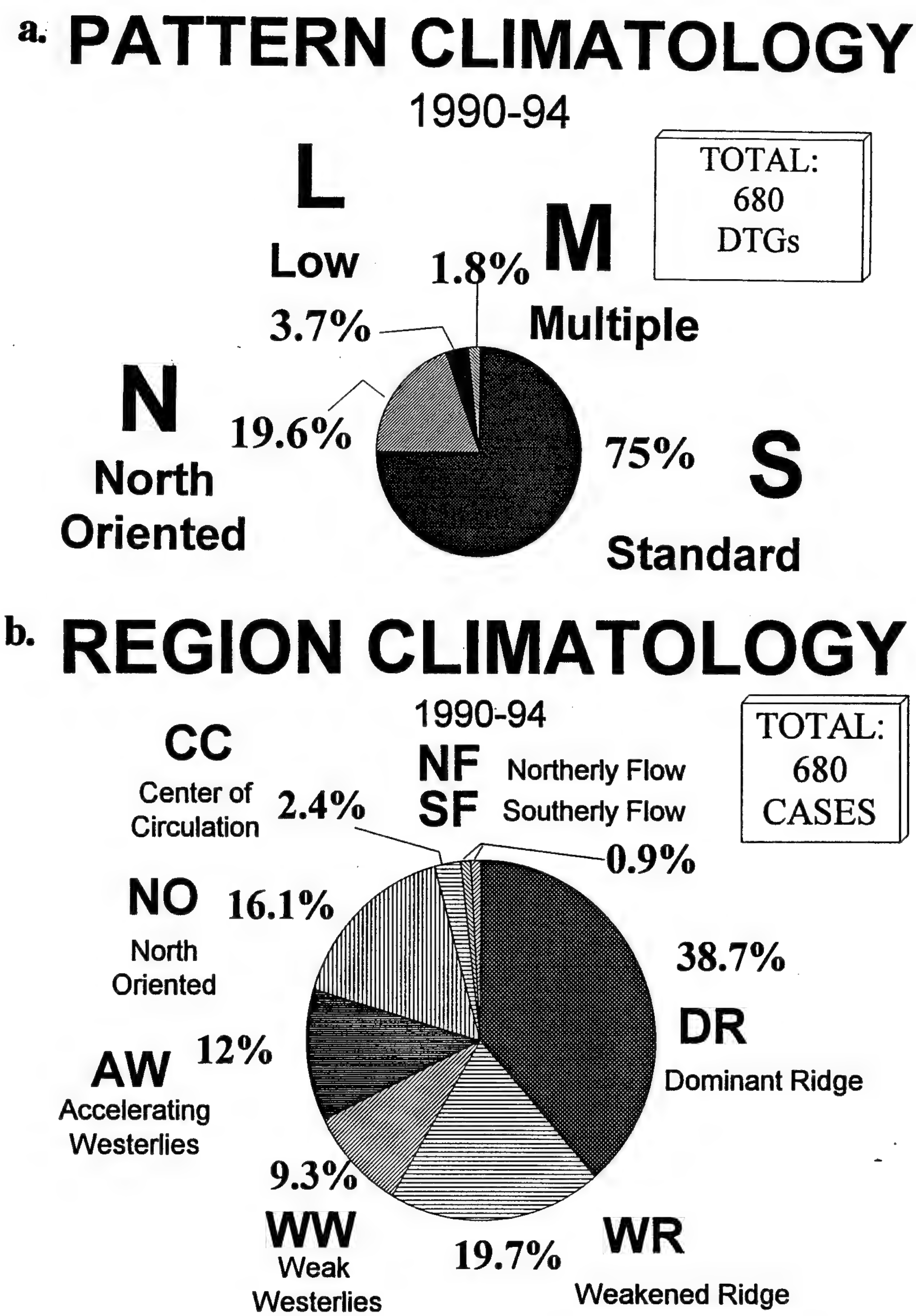

Figure 17. Percentage of the 680 DTGs in (a) Synoptic Patterns and (b) Synoptic Regions during 1990-1993 in the North Atlantic.

Regions (Table 3). Three of the Synoptic Regions are present in more than one Synoptic Pattern, so that the environmental steering should be similar within the Region. For example, the North-oriented (NO) Region is typified by a southerly steering flow, which is present in both the North-oriented (N) Pattern and on the eastern side of the Low (L) Pattern.

The Dominant Ridge (DR) Region comprises 38.7% of the classifications (Fig. 17b), which is almost twice the 19.7% in the Weakened Ridge (WR) Region. By contrast, TCs in the western North Pacific spend little time (3.9%) in the WR Region. However, the effects of SRM in the Atlantic tend to cause TCs to transition into or out of the WR Region much more easily and more often.

Although present in two Synoptic Patterns, the NO Region only encompasses 16.1% of the DTGs, which is down from the 24% observed in the North Pacific. Although the Accelerating Westerlies (AW) Region exists in three Synoptic Patterns (Table 3), one of which is hypothetical, it only constitutes 12% of the cases, which is comparable to the 14% of the cases in the North Pacific. The rapid translation speeds of TCs in this Region leads to the small percentage of cases. Although the Center of Circulation (CC) Region of the L Synoptic Pattern is only observed in two TCs, the several days in the Region in both cases results in a relatively high 2.4% of the total DTGs. Finally, the Multiple (M) TC Pattern only occurs in one instance when two TCs came close enough in the five-year sample, which results in both the Northerly Flow (NF) and Southerly Flow (SF) Regions contributing a small 0.9% of the cases.

c. *Pattern/Region Frequency*

In general, TCs in the same Synoptic Region, but in another Synoptic Pattern, will have a similar steering flow. However, the storm tracks may be slightly different because of the different large-scale environmental forcing. For example, TCs located in the N/NO and L/NO Pattern/Region combinations are undergoing the influence of a basically southerly environmental flow. The storm track in the N/NO Pattern/Region may vary clockwise from northwest to northeast depending on the tilt of the ridge. The track in the L/NO Pattern/Region will vary from northerly counter-clockwise to northwesterly due to the presence of the cyclonic circulation to the southwest. Accordingly, a summary of the Pattern/Region combinations (Fig. 18) is required to obtain a better overall climatological view.

The S/DR Pattern/Region combination is the most frequent at 38.6%, which is a decrease from the 50.8% frequency for the western North Pacific. Surprisingly, the second most common Pattern/Region combination is the S/WR at 19.8%, since this is an extremely large increase from the 3.9% frequency in the North Pacific. Whereas, the N/NO combination occurs in 17.5% of the North Pacific cases, the percentage decreases to 14.9% of the North Atlantic cases. The increased frequency of the S/WR and decrease of the N/NO combinations are attributable to the impact of SRM on the subtropical ridge. As discussed in Section E.1.b of this Chapter, the impact and effects of SRM in the North Atlantic appear to be much larger compared to the western North Pacific. The larger impact of SRM is further supported by the 9.3% of the cases characterized as S/WW, which is not identified in the western North Pacific.

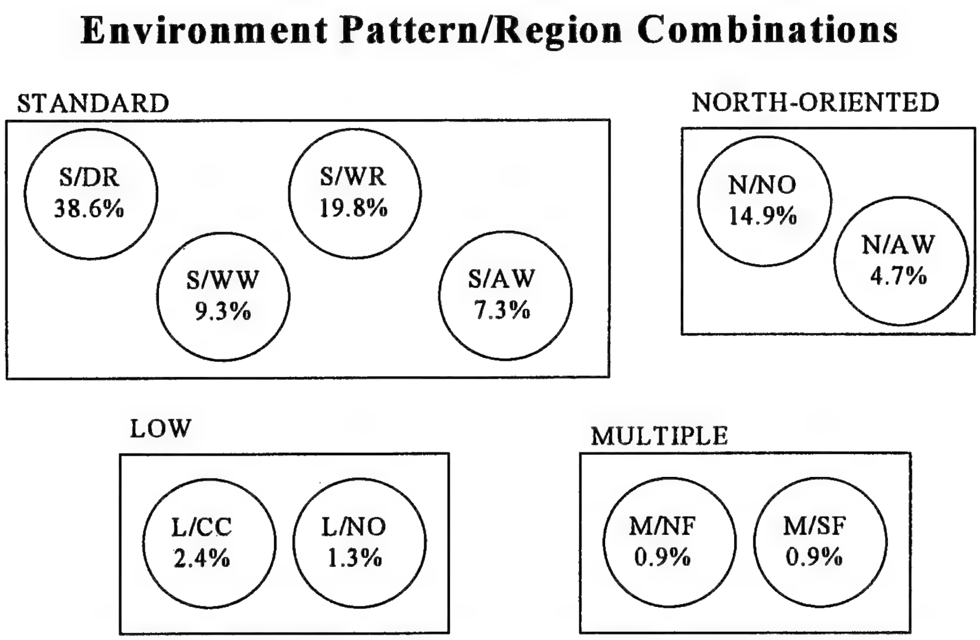

Figure 18. Climatology of Synoptic Pattern/Region combinations in the North Atlantic during 1990-1994.

The S/AW combination was observed in 7.3% of the Atlantic cases while the N/AW was observed in 4.7% of the cases. By contrast, the S/AW combination was observed about one-third as often as N/AW in the western North Pacific, which Carr et al. (1995) attributed to the rarity of the Environment Structure changing from the N to the S Pattern once a storm reaches the AW Region. However, SRM can cause the North Atlantic Environment Structure to change from a N Pattern into a S Pattern, while the TC remains in the AW Region.

Four Synoptic Regions are defined in the Low (L) Pattern (Fig. 8), although only two of these Regions were actually observed in the five-year sample. The L/CC Pattern/Region only occurred during two TCs, which accounts for 2.4% of the

cases. The pre-TC disturbances identified in the CC Region tend to exist for several days. While the L/NO combination is observed in three TCs, this accounts for a smaller 1.3% of the total cases. The larger scale cyclonic circulation that is advecting the TC tends to dissipate within 36-48 h, which results in a smaller number of DTGs characterized in the L/NO Pattern/Region combination.

As discussed above, the M Pattern is only observed with one storm event in this five-year sample. The low 0.9% frequency for the M/NF and M/SF combinations is attributable to the relative infrequency with which the separation distance between two TCs in the North Atlantic is less than 20° lat. However, a forecaster must be alert to this rare possibility whenever two TCs are existing, because the potential for anomalous tracks is high in these cases.

The simple percentages of the overall sample of assignments discussed above do not reflect the differing lengths of time that a TC may spend in the varying Pattern/Region combinations. While some assignments persist for a week, others only last for one 12 h period. The length of time in each Pattern/Region will vary because the horizontal domain of each Pattern/Region varies greatly, the translation speeds through each Pattern/Region differ, and some Environment Structures are dissipative. Therefore, some Pattern/Region combinations may appear to be under-represented and give a forecaster the wrong impression as to the relative importance of a particular Pattern/Region.

An alternate method for counting Environment Structures in the five-year sample is to count each Pattern/Region occurrence separately, regardless of how long the

TC remains in that Pattern/Region. This method of counting reduces the 680 DTGs for the 57 TCs to a total of 176 assignments (Table 4b). Only three Synoptic Pattern/Region combinations have a significant change in their percentages of occurrence with the new counting method. The S/DR combination is reduced from 38.6% (Table 4a) to 30.1% (Table 4b) of the occurrences because of the long periods that many TCs spend in this Pattern/Region. Over half of the reduction in the S/DR combination is compensated by an increase in the S/WR combination as it increases from 19.8% (Table 4a) to 24.4% (Table 4b) of the total occurrences. The final significant change is in the S/WW percentages that increases from 9.3% (Table 4a) to 11.9% (Table 4b). The increase in the S/WR and S/WW percentages is consistent with SRM causing TCs to transition into and out of these Pattern/Region combinations over periods as short as 12 h. While the percentages for occurrences of the other Pattern/Region combinations do change, none of the percentage changes have a significant impact on the prior frequency estimates.

d. Seasonal Variations

The large-scale environment changes as the hurricane season progresses from the official opening on 1 June to closure on 30 November, which results in seasonal trends in the Synoptic Patterns and Regions (Fig. 19). In this five-year (1990-1994) sample, TCs were observed in every month of the official hurricane season, and two TCs occurred in May. Although the S Pattern has the highest occurrence percentage in each month, the percentage drops from a high of 100% in May to a low of 61% in November.

Table 4. (a) Number of the 680 DTGs the TCs are in the Synoptic Pattern/Region. (b) Number of times (regardless of duration) the 57 TCs are in the Pattern/Region combination.

a

		%
S/DR	262.5	38.6
S/WR	134.5	19.8
S/WW	63.5	9.3
S/AW	49.5	7.3
N/NO	101	14.9
N/AW	32	4.7
L/CC	16.5	2.4
L/NO	8.5	1.3
M/NF	6	0.9
M/SF	6	0.9
	680	

b

		%
S/DR	53	30.1
S/WR	43	24.4
S/WW	21	11.9
S/AW	14	8
N/NO	28	15.9
N/AW	10	5.7
L/CC	2	1.1
L/NO	3	1.7
M/NF	1	0.6
M/SF	1	0.6
	176	

The "step-wise" decrease in occurrence to about 87% for the months of June and July, to about 77% for the months of August and September, and about 62% for October and November, is curious, but may be simply due to the small sample.

The month-by-month increases in the N Pattern almost matches the decreases in the S Pattern occurrences. That is, the frequencies of N Pattern increases from about 13% for June and July to about 18% for August and September, and about 28% during October and November.

Although the combined N and S Patterns are the only two Patterns that occur in May, June, and July, the L and M Patterns are increasingly present from August through November. During October and November, the L Pattern accounts for 9.2% and 10% of the cases. This seasonal increase in the TC frequency in the L Pattern is consistent with its formation from an upper-level low developing downward to the

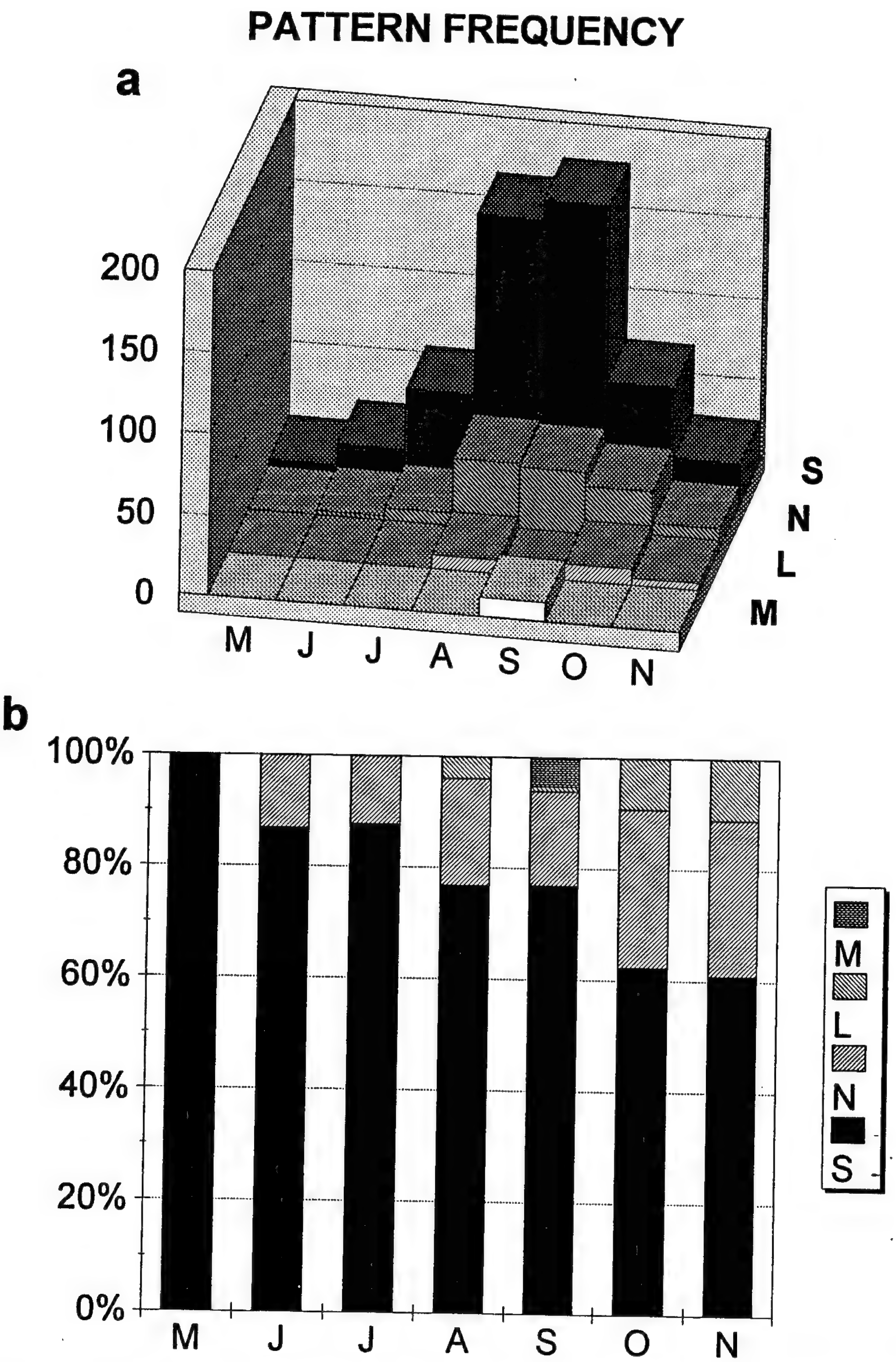

Figure 19. Monthly (a) occurrences and (b) percent frequency of the Synoptic Patterns in North Atlantic TCs during 1990-1994.

surface. In the last two months of the Atlantic tropical season, the mid-latitude weather systems appear to push farther south and increase in strength over a tropical/subtropical ocean with T>26°C. Whereas similar strength mid-latitude systems also penetrate into the subtropics/tropics in the early season, the sea-surface temperatures have not increased to the required 26°C at this time. In addition to promoting TC formations, the greater amplitude of the late-season mid-latitude systems greatly affects the appearance and strength of the subtropical ridge.

2. Tracks

The importance of assigning accurately Environment Structure in the Systematic Approach is illustrated by summaries of TC tracks in each Pattern/Region combination. The tracks in the S Pattern are generally as expected (Fig. 20). Tracks associated with the S/DR Pattern/Region are basically long, east-to-west tracks south of 30°N, normally with an increase in latitude as the TC proceeds to the west.

Three cases of TCs characterized as S/DR have a north-northwestward track, although two cases last only for 12-24 h. The third case is Hurricane Isidore during 1990, which is a very unique case of S/DR due to the alignment of the subtropical ridge. Hurricane Isidore developed on 4 September from a vigorous tropical wave at 7°N just off the coast of Africa (NHC 1990a). A mid-tropospheric cyclonic circulation developed off the northwest coast of Africa on 4 September and remained entrenched in the region until it began to dissipate on 7 September. The mid-tropospheric cyclonic circulation caused the subtropical ridge to assume the shape of a horseshoe to the north of Isidore with a weak cyclonic circulation in the center (Fig. 21). As a result, Hurricane Isidore

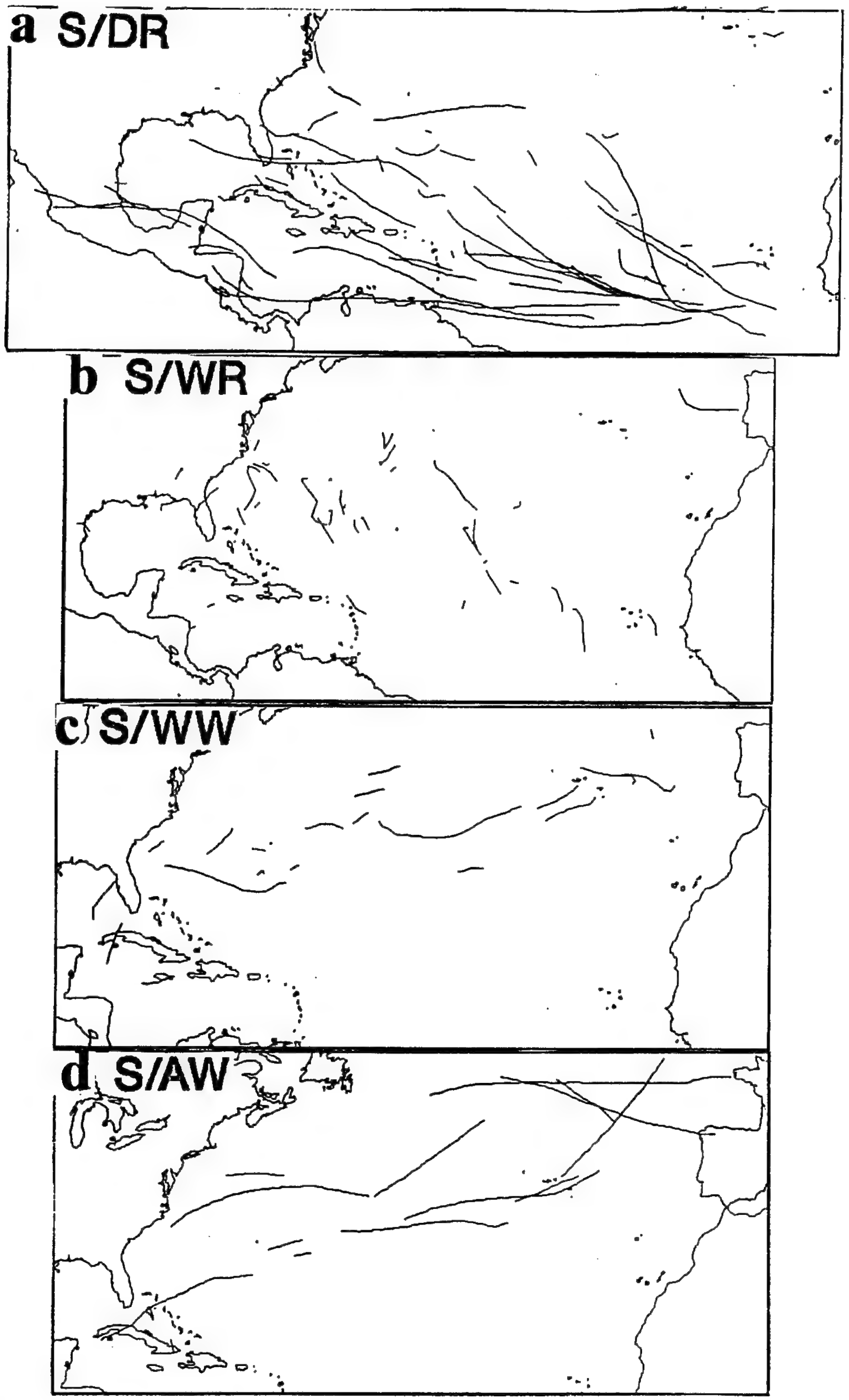

Figure 20. Storm tracks during 1990-1994 while the storm is in the Standard Pattern and the (a) Dominant Ridge, (b) Weakened Ridge, (c) Weak Westerlies, and (d) Accelerating Westerlies Regions.

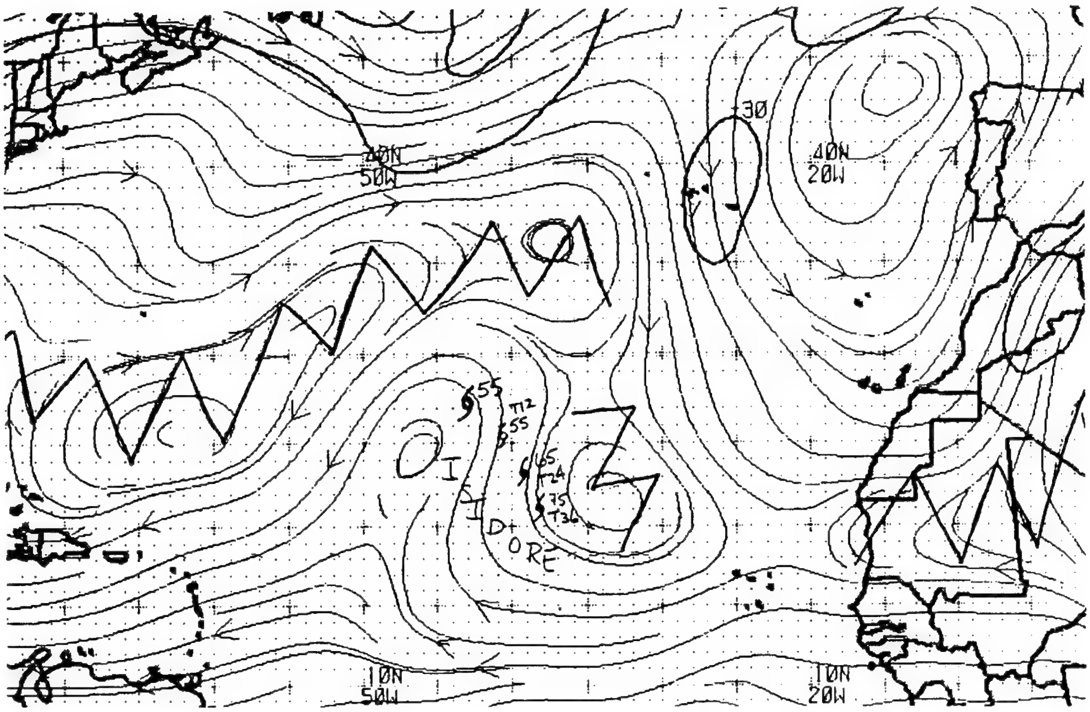

Figure 21. NOGAPS 500 mb streamline and isotach analysis for Hurricane Isidore at 1200 UTC 9 September 1990 with present and past 12-, 24-, and 36-h positions.

begins a northwestward and then north-northwestward track as it is advected by the 500 mb environmental steering, which brings the TC to the top center of the horseshoe pattern. Although Hurricane Isidore is moving northward, the subtropical ridge is still dominating the environmental steering flow, perhaps with the addition of some beta effect propagation (BEP).

The S/WR tracks (Fig. 20b) are typically very short, mostly toward the northwest to northeast. Some of the S/WR tracks are toward the southeast to southwest direction because of SRM. These TC tracks are expected as a TC either is moving through the subtropical ridge or is being forced back into the ridge. The one exception is Hurricane Bob during 1991 which proceeds up the west side of the subtropical ridge, eastward over

the north-south axis, and then continues southeastward toward the subtropical ridge axis before transitioning to a S/WR combination again. As Hurricane Bob approaches Spain and Portugal as an extratropical storm, it moves less than 7 kt to the southeast and then east.

As expected, tracks associated with the S/WW Pattern/Region are northeastward clockwise to southeastward (Fig. 20c). TCs in this Pattern/Region are located on the north side of the subtropical ridge with translation speeds less than 15 kt. Although the majority of the storm tracks are located between 30° and 40° N and are short, two longer tracks are found in this Pattern/Region. The S/AW tracks (Fig. 20d) are typically long because of the persistence of the TC while the translation speeds are in excess of 15 kt.

The North-oriented Synoptic Pattern has two Regions that have very consistent TC tracks (Fig. 22). The north-south orientation of the combined peripheral ridge and subtropical ridge results in storm tracks in the NO Region (Fig. 22a) that are primarily to the north-northeast. Two cyclones have a northwestward track because the ridge is tilted with a northwest-southeast orientation. Two-thirds of the storm tracks in this Pattern/Region are in the region from Mexico to Bermuda, which includes the east coast of the United States. With only two exceptions, the storm tracks in the N/AW Pattern/Region (Fig. 22b) are located between 40°W and 70°W and north of 35°N. This identifies a small region where the forecaster has to consider this Pattern/Region as being highly probable.

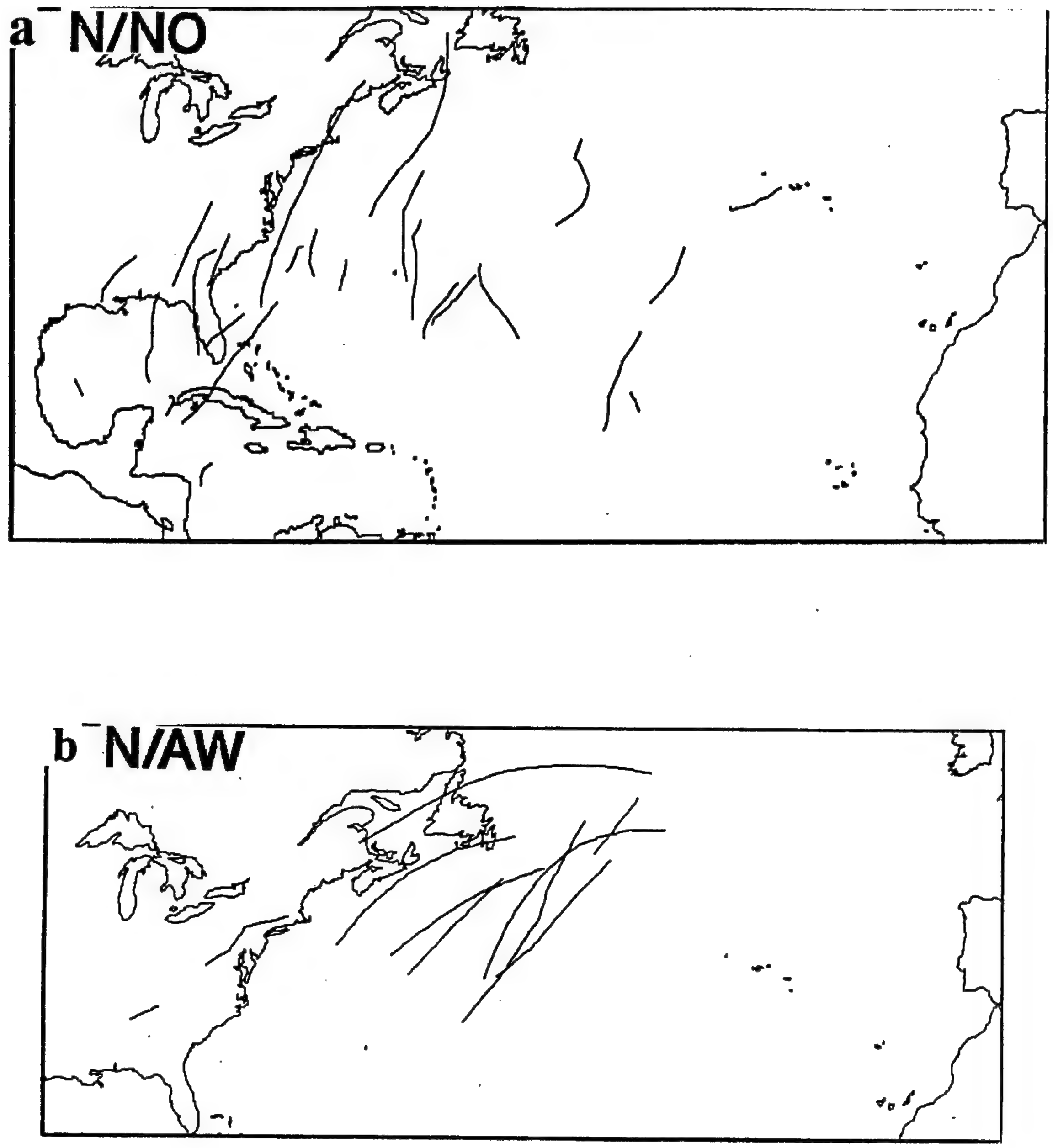

Figure 22. Storm tracks as in Fig. 20, except in the North-oriented Pattern and the (a) North-oriented and (b) Accelerating Westerlies Regions.

A total of five TCs in the L Synoptic Pattern occurred in the five-year sample, with the tracks in Fig. 23. As previously discussed, the two L/CC storm tracks are from the west to the southwest (Fig. 23a). The L/NO storm tracks (Fig. 23b) have all three possible orientations in the Pattern/Region. One track is heading north, another has a circular track around the cyclonic circulation, and one almost straight track has a northwesterly direction as the cyclonic circulation and TC move relative to one another.

3. Synoptic Pattern/Region Transitions

A "complete" transition is defined as when an actual change of either Synoptic Pattern, Synoptic Region, or both occurs. This is the only type considered for this discussion. The track of a TC is not expected to vary much while it remains within the same Synoptic Pattern/Region. A transition in the Environment Structure is expected to result in a TC track change. The forecaster must recognize when the Environment Structure is changing in order to forecast properly these track changes . The Environment Structure can change as the result of: (i) TC-Environment transformations (Fig. 3); (ii) changes in Environment Structure not principally dependent on the presence of a TC (Fig. 4); and (iii) simple advection of the TC by the environmental steering out of the Synoptic Pattern. The TC-Environment transformations specific to the North Atlantic are listed in Fig. 24.

In the western North Pacific sample, 248 transitions occurred with 30 different types of transitions observed (Carr et al. 1995). In comparison, the North Atlantic five-year sample only has 117 transitions, but experiences 24 different transitions among the Pattern/Region combinations. The complicated diagram in Fig. 25 includes all of the

Figure 23. Storm tracks as in Fig. 20, except in the Low Synoptic Pattern and the (a) Center of Circulation and (b) North-oriented Regions.

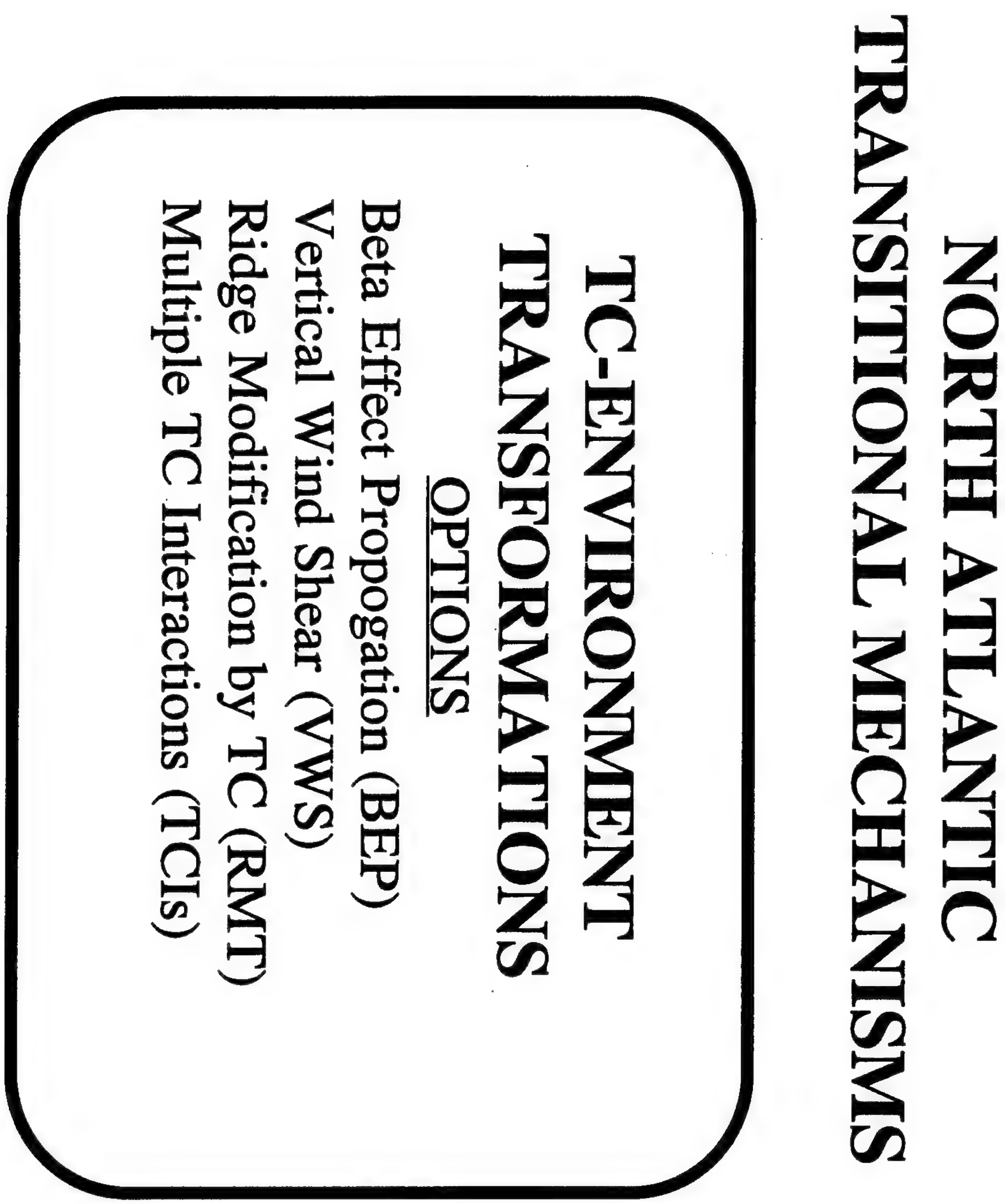

Figure 24. As in Fig. 3, except transitional mechanisms for the North Atlantic.

observed transitions and how many of each transition occurred. The number of transitions entering a Pattern/Region does not have to be equal to the number exiting the Pattern/Region because TCs can develop or dissipate within any of the Pattern/Region combinations.

The numbers in Table 4 indicate there are 176 Pattern/Region occurrences for 57 TCs in the five-year sample. These numbers seem to suggest that the average TC will undergo two transitions in their lifetime. However, 20 (35%) of the sample TCs undergo no transitions. Fifteen of these 20 storms remain in the S/DR combination during their entire lifetime. About one-half of these 15 storms last only three days or less. The remaining five storms with a single Pattern/Region combination include two N/NO, two S/WW, and one S/AW. Four of these cases are also short-lived TCs that exist less than two days. After subtracting the 20 TCs without a transition, the 37 TCs that do undergo a transition undergo an average of 3.2 transitions during their lifetimes. If a storm survives long enough to reach the mid-latitudes, where most transitions occur, it may have transitions in Environment Structure that present a potential serious forecast problem for the unaware forecaster.

All of the transitions are included in Fig. 25, because every possible transition must be considered by the forecaster, regardless of how rare it may transpire. However, the forecaster will focus most of his/her attention on those transitions that are "recurring," i.e., occur more than once. After removing those transitions that only occur once in the five-year sample, the number of transitions that the forecaster must consider is smaller, so that the forecast task becomes relatively simpler (Fig. 26). This transition diagram still

includes 107 (91.5%) of all transitions. After removing the TCs that do not undergo a transition and eliminating the transitions that are not recurring, the average number of transitions a TC will undergo in its lifetime is still 2.9.

Even though the computations in the discussion below will not include the singular transitions in order to concentrate on the recurring transitions, this should not be

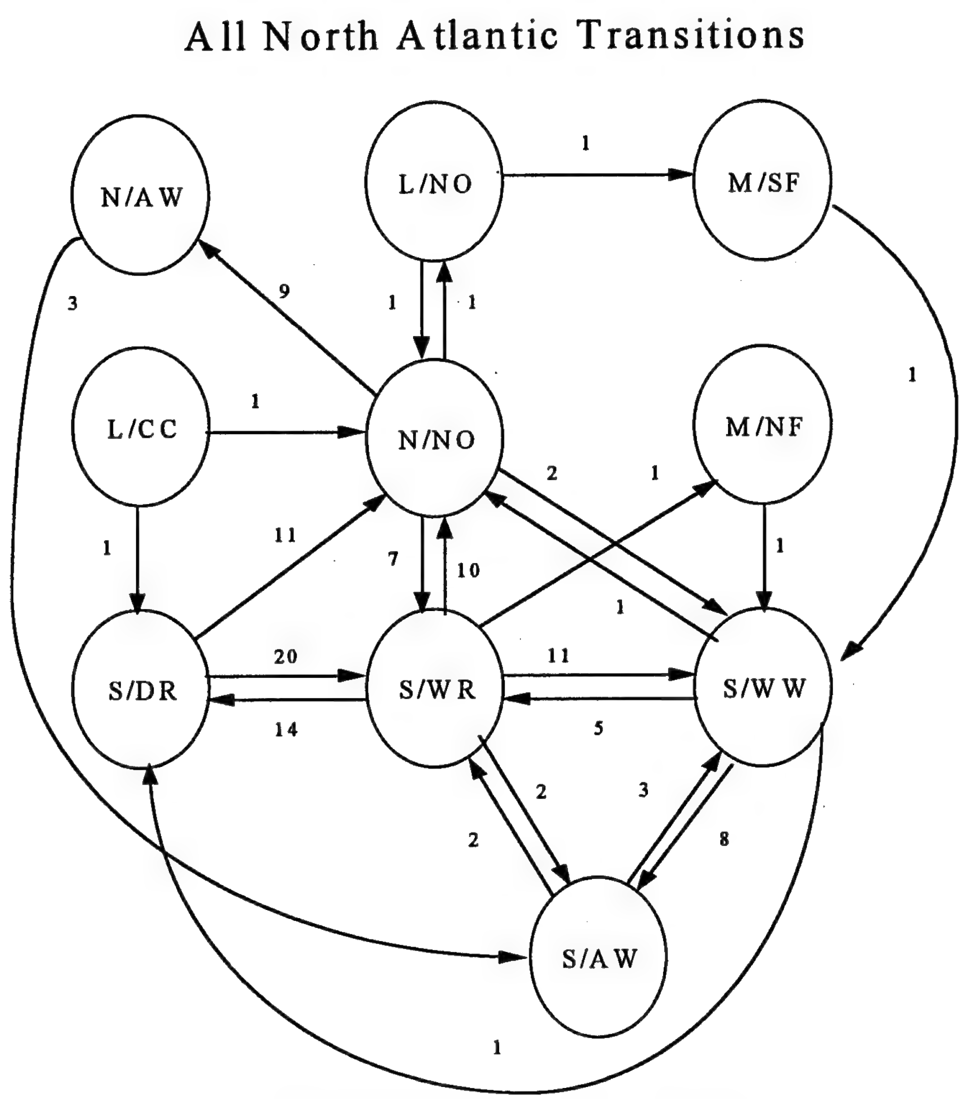

Figure 25. All transitions between Synoptic Pattern/Regions for the five-year sample. The numbers represent how many times the transitions occurred.

interpreted that the singular transitions are of no importance to forecasting TC track motion. The 107 transitions represent a TC moving from one Pattern/Region combination to a different Pattern/Region combination. Therefore, there are 214 Pattern/Region combinations involved in the transitions.

Surprisingly, the Pattern/Region most commonly involved in transitions is the S/WR combination, even though only 43 (24.4%) S/WR cases occur in the five-year sample (Table 4). This Pattern/Region is involved in 71 of the 107 (66.4%) recurring transitions (Fig. 26), which is more than ten percent higher than any Pattern/Region in the western North Pacific (Carr et al. 1995). Thus, this Pattern/Region is the most important one for an Atlantic forecaster to consider. As shown in Fig. 26, the 71 transitions from S/WR involve four other Pattern/Regions; S/DR, S/WW, S/AW, and N/NO. Of these 71 transitions, 37 are transitions out of and 34 are transitions into the S/WR Pattern/Region.

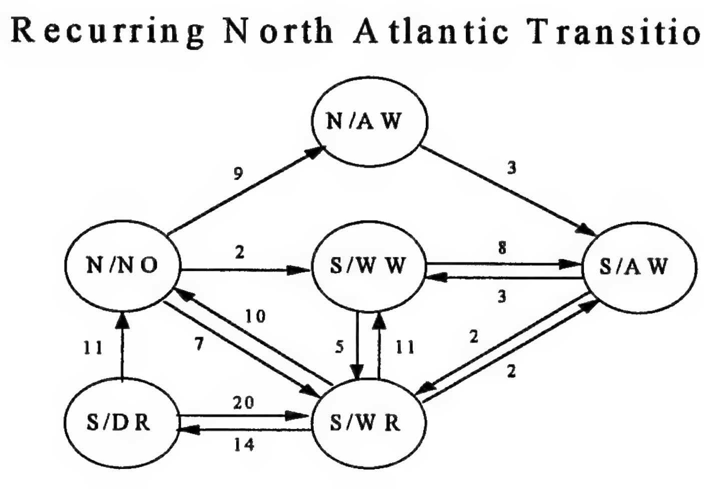

Figure 26. Recurring (i.e., more than one occurrence) transitions between Synoptic Pattern/Regions. The numbers represent how many times the transition occurred.

Only the S/DR Pattern/Region has more transitions into S/WR than return to it. The S/WR to S/AW transitions have equal numbers each way, but this only involves a total of four transitions. Finally, four TCs dissipate while in the S/WR combination.

Of the 34 transitions into S/WR (Fig. 26), almost 60% are from S/DR, which is the Pattern/Region from which TCs are expected to transition. A normal recurvature sequence in the S Pattern of S/DR to S/WR to S/AW as in the western North Pacific (Carr et al. 1995) is relatively rare in the Atlantic as only two transitions from S/WR to S/AW occur in the five-year sample. One recurvature-type transition from S/WR is via S/WW (11 cases, 29.7%) to S/AW (8 cases). The transition to S/WW would occur through a combination of beta-effect propagation (BEP) and advection by the environmental steering. Another recurvature-type transition from S/WR is via N/NO (10 cases, 27%). However, the most common transition (14 cases, 30%) is back to a S/DR combination, which can be viewed as a failed recurvature. Track forecast errors can be very large in such a failed recurvature case if a recurvature forecast is made. This can be identified as one of the reasons why forecasting TCs in the Atlantic can be quite difficult. A transition from S/WR to either S/DR or N/NO typically involves some type of SRM. The phasing with the passing mid-latitude trough/ridge system is one of the determining factors as to which transition will occur. If the SRM is in phase with or amplifies the ridge to the east of the TC, the transition will be to N/NO. If the mid-latitude phasing re-establishes a ridge to the north, the transition will be back to S/DR. In six instances in which a TC transitioned into S/DR from S/WR, it then dissipated.

Since this transition from S/WR is the only one to S/DR (14 cases), a TC transitioning into S/DR has a 40% chance of dissipating in the S/DR Pattern/Region.

The S/DR Pattern/Region occurred 53 times (Table 4) in the five-year sample. Of these 53 cases, no transition occurred 15 times. The most common transition (20 cases, 37.7%) from S/DR is to S/WR, although the reverse transition from S/WR back into S/DR occurs 14 times (Fig. 26). As indicated above, this sequence would be viewed as a failed recurvature. This means there were instances of multiple transitions between S/DR and N/NO or S/WR. Based on this small sample, the possibility of a TC transitioning out of S/DR will have a 11/31 chance of going to N/NO versus a 20/31 chance of going to S/WR.

The S/WW Pattern/Region had 21 (11.9%) occurrences (see Table 4) and was involved in 29 transitions (Fig. 26). In two cases, the TC formed and dissipated in the S/WW combination, and thus was in S/WW for its entire existence. In 16 of the 29 transitions into S/WW, 11 come via the expected route of S/WR. Three other transitions into S/WW are from S/AW, which is again a failed recurvature. In four of the 16 (25%) transitions into S/WW, the TC dissipated. The 13 transitions from S/WW only go to two Pattern/Region combinations, a progression to S/AW or a return to S/WR. As indicated above, the likelihood of transition from S/WW to S/AW to complete the recurvature is 8 of 13 (62%), whereas 38% transition back to S/WR because of mid-latitude interactions via SRM.

With 28 (15.9%) occurrences (Table 4), the N/NO combination is the third most frequent to occur and is involved in 38 (36.4%) of the transitions (Fig. 26). In two storms

that only lasted 1-2 days, the TC began and remained in the N/NO combination. The 21 transitions into the N/NO Pattern/Region are evenly distributed between S/DR and S/WR. As discussed in Section D.2 of this chapter, the SRM transformation mechanism is responsible for the majority of these transitions into N/NO. Only two to three of the S/DR to N/NO transitions are caused by Ridge Modification by TC (RMT). In six cases of the TC has transitioning into N/NO, the TC subsequently dissipated or became extratropical. If the TC does transition from N/NO, the most common (50%) is the expected transition to N/AW. However, the other 50% of the transitions are to a S Pattern, with seven of nine to S/WR. Since both S/WR or S/WW also have northward tracks, these transitions are not likely to result in a track direction change. Rather, the subtropical ridge is more clearly the primary contributor to the continued northward track instead of the N Pattern.

Transitions into the S/AW Pattern/Region can occur from either S/WW (61.5%), S/WR (15.4%), or N/AW (23.1%) (Fig. 26). The transitions from S/WW and S/WR are expected as part of normal recurvature of the TC. Whereas the N/AW to S/AW transition was not observed in the western North Pacific, three such transitions occurred in the North Atlantic via the SRM transformation. The five transitions out of S/AW are also unusual relative to the western North Pacific where transitions out of the S/AW Region were not observed (Carr et al. 1995). This transition from S/AW is the effect of SRM that can cause a TC to move southward toward the subtropical ridge and a return to either S/WW or S/WR. In eight instances in which the TC transitioned into S/AW, it either dissipated or a transformation to an extratropical cyclone occurred.

The final Pattern/Region involved in "recurring" transitions is N/AW. All nine of the transitions into N/AW are from N/NO. When a TC is in the N/AW Pattern/Region there is a 70% probability the storm will dissipate. If it does transition from N/AW, it will only go to the S/AW Pattern/Region as a result of the SRM transformation. This transition may change the track direction, but the TC is still likely to be dissipating.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Carr and Elsberry hypothesized that the meteorological framework of the Systematic Approach would be generally applicable to other tropical basins of the world. The Systematic Approach was tested to see if the meteorological framework was applicable to the North Atlantic. While the CE Systematic Approach from the western North Pacific was used as a starting point, an examination of all Atlantic TCs from 1990-1994 resulted in some modifications and variations in the Environment Structure and TC-Environment transitional mechanisms being developed. In addition to not finding any monsoon Gyre (G) Patterns, the N Synoptic Pattern was modified for the Atlantic. Although the western North Pacific North-oriented (N) Pattern was observed in a few cases, an Atlantic North-oriented Synoptic Pattern was generated because of the variations in its appearance and the formation dynamics involving Subtropical Ridge Modification (SRM). More importantly, an entirely new Low (L) Synoptic Pattern was developed. The L Pattern was determined to be a recurring Environment Structure that required explanation. A new Weak Westerlies (WW) Synoptic Region in the S Pattern was also defined. The WW is an intermediary between the Weakened Ridge (WR) and Accelerating Westerlies (AW) Regions.

A five-year (1990-1994) of North Atlantic TCs was used to calculate the Pattern, Region, and Pattern/Region frequencies and a transition climatology for the North Atlantic. The S Pattern is the most prevalent (74.9%) Pattern. The L (3.7%) and M

(1.8%) Patterns are relatively uncommon in this data sample. While the DR Region is almost twice as common (38.7% compared to 19.7%) as any other single Region in the North Atlantic, it is not as common as it was in the western North Pacific (54%). As a result of the increased effects of SRM, the S/WR Pattern/Region (19.7%) is almost five times more common than it was in the western North Pacific (4%). Since the L and M Patterns are relatively rare, the CC, NF, and SF Synoptic Regions also have low frequencies of occurrence. Some distinct seasonality in the Pattern frequencies is noted, with L and M Patterns only occurring in the mid- to late-season.

The storm tracks demonstrate a predominant direction of motion associated with each Pattern/Region. Storms in some Pattern/Regions are found only in certain areas of the North Atlantic Ocean. Such knowledge of storm tracks can prove to be invaluable in preparing a forecast.

The transition frequencies in this five-year period demonstrated that the Pattern/Region most often involved in transitions (66.4%) is the S/WR combination. Six of the ten Pattern/Region combinations account for over 90% of all the transitions that occurred. The remaining four Pattern/Regions are involved in transitions that occurred once in the five-year sample. One distinct difference in the Atlantic versus in the western North Pacific is the increased importance of the Subtropical Ridge Modification (SRM) by mid-latitude trough/ridge systems. This leads to more return transitions and unusual N Pattern to S Pattern and within-S transitions. These transitions account for many of the unusual TC tracks in the subtropics during 1990-1994.

In conclusion, the meteorological knowledge base of the Systematic Approach with some modification was determined to be very applicable to the North Atlantic. The Atlantic version of the knowledge base and the associated climatology can assist forecasters in better forecasting TC movement via: (i) prompt and consistent recognition of recurring environmental patterns in evolving global model fields; and (ii) association of characteristic TC forecast tracks with those patterns. This knowledge combined with an understanding of the forecast traits of the global numerical model and other objective track forecast aids that depend on the numerical model will allow the forecaster to improve upon the objective guidance in similar situations. While this tool will not guarantee a correct forecast, the Systematic Approach should prove to be of great assistance in the tropical basin with a lot of variation in its historical storm tracks.

B. RECOMMENDATIONS

Although the five-year sample demonstrates the applicability of the Systematic Approach to the North Atlantic, additional years are needed. Since the five years contained a total of 57 North Atlantic TCs, the frequencies of occurrences and the probabilities of transitions must be regarded as only a preliminary climatology. The addition of more years, especially the very active and unusual 1995 tropical season, is desirable to obtain more representative frequencies of the Patterns, Regions, Pattern/Regions, and transitions.

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